POST-RESTORATION EVALUATION OF TWO URBAN STREAMS IN AUSTIN, TEXAS, USA

A Thesis

by

MEGAN DRISKILL MEIER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Water Management and Hydrological Sciences

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Approved by:

Chair of Committee,	John R. Giardino
Committee Members,	Christopher C. Mathewson
	Ming-Han Li
Chair of Interdisciplinary Faculty,	Ronald A. Kaiser

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Major Subject: Water Management and Hydrological Sciences

ABSTRACT

Post-restoration Evaluation of Two Urban Streams in Austin, Texas, USA. (May 2008)

Megan Driskill Meier, B.S., Texas A&M University

Chair of Advisory Committee: Dr. John R. Giardino

Rapid urban growth of Austin, Texas, has resulted in significant alteration of the surface characteristics of the Colorado River Watershed. These changes have increased the runoff and accelerated erosion of the banks of stream channels. To minimize the threat of stream erosion to real estate and infrastructure, the City of Austin began restoring unstable channel reaches through the placement of rock armor on the banks, construction of rock grade controls, and planting of riparian vegetation. Since the late 1990s, approximately thirty channel reaches have been restored in the Austin area. Considerable discussion is taking place regarding the true impact of restoration on streams. Few studies have attempted to conduct post-project evaluation to assess the impact of restoration efforts. Because it has been several years since steps were taken to stabilize these streams, a sufficient time period for stabilization to occur has passed. Thus, we believe these projects now can be assessed for the temporal impact of restoration on these streams.

We studied the restored and natural reaches of two of these streams. The natural reaches served as ergodic surrogates for temporal channel development of the restored reaches. We used Rosgen's (2001) methodology of channel stability assessment and repeat ground photography (Graf, 1985) to evaluate the stability of Waller Creek and Tannehill Branch. Variables of channel morphology analyzed included riparian vegetation cover, vertical stability, scour/deposition potential, and bed sediment composition. From our analysis, restoration enlarged stream channels, decreased bank height ratios and reduced flood prone width. Bed sediment analysis revealed that pools contain a higher percentage of fines whereas riffles are coarser in restored reaches than pre-restoration reaches. Visual examination of ground photographs and scores from the Pfankuch channel stability evaluation indicate that restoration increased vegetative cover and deposition. Thus, restoration efforts worked on these two streams. Data from the assessments of stream channel stability provide the basis upon which longer-term monitoring and evaluation can be conducted. Knowledge gained from long-term monitoring can be used to improve the effectiveness of the current and future restoration projects in Texas and elsewhere.

DEDICATION

To my husband, Russell

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1. INTRODUCTION

This study analyzes two urban streams in Austin, Texas. Three restored reaches were chosen as they were constructed using similar techniques and occurred in park areas. This thesis contains two separate articles: one which focuses on the geomorphological aspects of the restoration projects and the second which takes more of an engineering approach.

Urbanization alters river channels. Researchers, beginning with Leopold and Wolman in the late 1960s, have studied the cause, magnitude, duration, and location of these alterations (Chin and Gregory 2005). Appropriately, this knowledge has been increasingly applied to stream restoration projects during the past ten years (Riley 1998). As restoration can be a vital step to reducing and reversing the negative impacts of anthropogenic activities (Berger, 1990; Lassettre, 1997), the practice of restoring streams becomes significant in heavily populated areas such as Texas, where 297 cities are predicted to double in population over the next fifty years (TWDB, 2006).

Austin, Texas, in particular, has attempted to restore many stream reaches degraded by urban expansion associated with population growth (City of Austin, 1995a). The City of Austin is one of many cities recently applying fluvial geomorphological principles to restore degraded urban streams (Kondolf et al., 2002). However, few studies have investigated what occurs post-restoration (Kondolf and Micheli, 1995), and whether these urban streams are able to achieve a more stable state (Booth, 2005). Thus, one has to ask: How effective have stream restoration efforts been at improving

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This thesis follows the style of Geomorphology.

stream stability in the Colorado River watershed in Austin, Texas?

The overall objective of this research was to evaluate the effectiveness of restoration practices on restored reaches of urban stream channels in Austin. To achieve this objective, we evaluated the stability of the stream channels using Rosgen's methodology of channel stability assessment (2001) and repeat ground photography. We hypothesized that the restoration practices employed in Austin were effective at restoring stream stability, because they were grounded in geomorphic principles.

2. REVIEW OF LITERATURE

2.1 Introduction

Three major themes comprise the literature concerning urban stream restoration. The first addresses the physical and biological impacts of urbanization on streams. The second theme focuses on efforts to restore degraded urban streams, emphasizing what an effective restoration plan might include. The third theme centers on post-project monitoring and results of urban stream restoration projects from across the United States. These themes are summarized in the following section.

2.2. Geomorphology of Urban Streams

Streams in urban environments typically exhibit symptoms of what Meyer and others (2005, p. 602) termed the "urban stream syndrome". Symptoms include increased runoff, increased bankfull magnitude and frequency, increased water temperature, increased sediment and pollutant runoff, channel instability, erosion, creation of homogeneous aquatic habitat, reduced base flow, and minimization of interactions between the stream and the floodplain (Booth, 1990; Paul and Meyer, 2001; Carpenter et al., 2003; Davis et al., 2003; Allan, 2004; Walsh et al., 2005a). Initially, construction activities result in increased sediment delivery to streams, leading to a reduction in channel cross-sectional area from deposition of sediments (Wolman, 1967). After construction is complete, the increasing impervious area results in reduced infiltration and increased discharge, leading to channel enlargement through incision and expansion (Wolman, 1967; Hammer, 1972; Booth, 1990). Channel enlargement can also be the result of roads and stormwater infrastructure functioning as first-order streams. This infrastructure reduces time of concentration, which magnifies the peak flow magnitude and frequency of higher order streams (Marsh and Marsh, 1995; Walsh et al., 2005a).

Many studies have shown that channel enlargement has occurred in a variety of urbanized environments, including chalk and shale riverbeds (Allen and Narramore, 1985) and alluvial streams (Harris, 2002) in Texas, forested mountain streams in the Cascade Foothills of western Washington (Booth, 1990), ephemeral streams in central Arizona (Chin and Gregory, 2001, 2005), gravel-bed rivers in Pennsylvania (Hammer, 1972; Pizzuto et al., 2000), and alluvial streams in Mississippi (Shields et al., 1998). On a world scale, channel enlargement is typically 2-3 times and as much as 15 times for humid-temperate rivers (Chin, 2006).

Channel enlargement can be spatially and temporally variable within a watershed, with the stream sometimes “recovering” downstream (Chin and Gregory, 2001; Baron et al., 2002; Gregory, 2002; Harris, 2002; Allan, 2004; Booth, 2005). In Fountain Hills, Arizona, Chin and Gregory (2001; 2005) discovered a spatial pattern of adjustment in which channel enlargement occurred immediately downstream of road crossings because of increased stormwater runoff delivered from roads. Allen and Narramore (1985) found that streams with vegetation present, either in-stream or on the banks, reduced enlargement downstream because of increased aggradation. The channel area of Town Branch Creek increased within the town of Madisonville, Texas but, downstream of the town, channel area decreased to a size smaller than the natural reference stream (Harris, 2002).

2.3 Restoring Urban Streams

Recognition of the detrimental effects of urban development on the geomorphology and ecology of streams has led to efforts to restore urban streams (National Research Council, 1992; Kondolf et al., 2002). Stream restoration has been especially prominent in California and the Pacific Northwest of the United States, as well as in the United Kingdom. In the United States alone, reported river restoration costs averaged more than $1 billion per year from 1990-2003 (Bernhardt et al., 2005). Examples of successful restoration efforts include Baxter Creek in El Cerrito, California, which was restored to a pre-culverted condition using step pools and soil bioengineering techniques (Purcell et al., 2002). In the Puget Sound region of Washington, many restoration projects involve large woody debris to enhance fisheries and control both flood and sediment discharge (Schauman and Salisbury, 1998; Larson et al., 2001). Risk from erosion damaging structures on Tilmore Brook, UK, as well as the need to protect a wildlife corridor, resulted in restoration that minimized the use of "hard" engineering measures (Brookes et al., 2005).

Few other restoration projects have been as successful as those described above; in fact, many have failed to meet project objectives, mainly as a result of inadequate planning (Kondolf and Micheli, 1995). An effective restoration plan should include the following steps: (1) develop specific objectives; (2) analyze historical and current conditions; (3) design and construct the project; (4) collect and disseminate post-project results (Kondolf, 1995; Kondolf and Micheli, 1995; Downs and Kondolf, 2002; Carpenter et al., 2003; Lake, 2005). The complex nature of urban aquatic systems necessitates that a restoration plan also incorporates a variety of perspectives, including engineering, hydrology, geomorphology, ecology, sociology, and economics (Dunne and Leopold, 1978; Nolan and Guthrie, 1998; Baron et al., 2002; Carpenter et al., 2003; Palmer and Bernhardt, 2006).

The most complex step of the restoration plan is often the design. The design needs to address several issues, including the scale of the restoration project, whether process or only form is restored, and the level of societal involvement. Most restoration designs have been applied at the reach scale in a piecemeal fashion to provide instant, local solutions (Shields et al., 1998; Gregory and Chin, 2002; Rosgen, 2004; Booth, 2005; Lake, 2005; Palmer et al., 2005; Wohl et al., 2005). Reach-level designs focus on the importance of localized habitat variations needed for local species assemblages (Davis et al., 2003; Allan, 2004; Niezgoda and Johnson, 2005). Also, small-scale projects are less complex and provide results faster, thus allowing for quicker determination of failures and the need for adaptation of project design (Schauman and Salisbury, 1998; Lake, 2005).

Reach-level designs usually include planting riparian vegetation and/or installing in-stream structures. Riparian vegetation is beneficial as it buffers pollutant and sediment delivery, provides wildlife habitat, increases infiltration, stabilizes banks, and improves the aesthetic value of stream channels (Ellis, 1995; Smith, 1997; Paul and Meyer, 2001; Hancock, 2002; Kondolf et al., 2002; Li and Eddleman, 2002; Price and Birge, 2005). Some studies have even suggested that vegetation could improve water quality through trees providing shade that minimizes sunlight reaching the water, thus reducing algae abundance (Harremoes et al., 1996; Suren et al., 2005). Vegetation, once it is established, is also more resistant to erosion than “hard” structures, such as concrete (Li and Eddleman, 2002). The slow rate of vegetation establishment, however, has been cited in several studies as the reason for failure of in-stream structures (Kondolf and Micheli, 1995; Smith, 1997). New options, such as dormancy extension, are being examined to improve the rate of vegetation establishment, especially in warm environments (Li et al., 2005).

In-stream structures, such as boulders, pools, riffles, and large woody debris reduce channel degradation through decreasing channel slope and flow velocity (Smith, 1997; Brookes et al., 2005). These structures result in a decrease in erosion and sedimentation rates (Booth, 1990; Kondolf et al., 2002). These structures also increase habitat diversity and improve nutrient cycling by decreasing the removal of organic matter (Maughan and Nelson, 1980; Shields et al., 1998; Paul and Meyer, 2001; Groffman and Dorsey, 2005; Meyer et al., 2005). However, magnified flood frequency and magnitudes in urban environments can remove these structures or leave some, such as large woody debris, stranded above newly eroded channels (Booth, 1990; Paul and Meyer, 2001; Groffman and Dorsey, 2005).

To improve the survival rate of reach-level efforts, restoration designs also need to incorporate catchment management design to reduce runoff velocity and volume before it reaches the stream reach (Maughan and Nelson, 1980; Ellis, 1995; Helfield and Diamond, 1997; Larson et al., 2001; Groffman and Dorsey, 2005; Guilfoyle and Fischer, 2006). Catchment management includes floodplain “best management practices”

(BMPs), such as maintaining the riparian corridor, creating upland buffers, managing wetlands, and creating stormwater retention or detention ponds (Booth, 1990; Helfield and Diamond, 1997; Chin and Gregory, 2001; Hancock, 2002; Allan, 2004; Palmer et al., 2005; Walsh et al., 2005b; Kasahara and Hill, 2006). Marsh and Marsh (1995) also suggest creating development ordinances that minimize stream road crossings and minimize direct connection of impervious surfaces to streams to reduce the impacts of runoff. The use of these BMPs will vary because catchment processes affect reaches differently depending on the location of the reach in the catchment, the degree of urbanization, and the length of time the catchment has been urbanized (Hammer, 1972; Smith, 1997; Doyle et al., 2000; Paul and Meyer, 2001; Allan, 2004). Because channel reach processes are connected to catchment scale processes, restoration designs should be developed that integrate multiple reach-scale projects into a catchment-wide management plan (Ellis, 1995; Shields et al., 1998; Rhoads et al., 1999; Gregory and Chin, 2002; Chin and Gregory, 2005; Grimm et al., 2005; Lake, 2005).

An additional design challenge is the need to restore both form and process to the channel. Geomorphic parameters, such as channel width, capacity, and slope, are essential for designing a new channel morphology that can withstand the frequent floods in an urban environment and still provide habitat diversity (Ellis, 1995; Kondolf and Micheli, 1995; Nolan and Guthrie, 1998). Ecological parameters, however, are also vital to a design to guarantee that processes, and not just form, are restored (Shields et al., 1998; Palmer et al., 2005; Palmer and Bernhardt, 2006). Restoration of form alone may neglect one or more processes needed for the stream to return to a more resilient, stable state (Lake, 2005; Niezgoda and Johnson, 2005; Ryder and Miller, 2005). Restoration of processes, as well as biological complexity, is also needed for aquatic ecosystems to continue to provide services beneficial to society, such as flood control and purification of wastes (Baron et al., 2002; Kondolf et al., 2002; Meyer et al., 2005).

The last issue that should be addressed during the design phase is societal involvement (Schauman and Salisbury, 1998; Rhoads et al., 1999). It is essential for the sustainability of a restoration plan that society is involved and plays a supportive role (National Research Council, 1992; Schauman and Salisbury, 1998; Rhoads et al., 1999; Booth, 2005; Wohl et al., 2005; Palmer and Bernhardt, 2006). Society involvement can include actual assistance with design and construction, such as in the Stream Doctor project (Middleton, 2001), or merely the enhancement of educational programs on the ecological, aesthetic, and recreational benefits of stream restoration (Dunne and Leopold, 1978; Middleton, 2001; Purcell et al., 2002; Carpenter et al., 2003). Education of the public on the role of storm drains in stream pollution contributed to the improvement of water quality and successful restoration of Strawberry Creek on the University of California-Berkeley campus (Charbonneau and Resh, 1992). Public opinion should be assessed early in the planning process (Tunstall et al., 2000; Brookes et al., 2005; Chin and Gregory, 2005), so that the project is customized not only for the hydrologic conditions present, but also for the surrounding community (Wolman, 1967).

Ideally, attempts to implement the restoration design should not occur until channel enlargement slows or stops following land use changes (Booth, 1990), so that new equilibrium conditions can be assessed. However, the flashiness of the urban stream hydrograph can prolong recovery times and can lead to a possible permanent state of disequilibrium (Wolman, 1967; Lake, 2005; Niezgoda and Johnson, 2005; Chin, 2006). Stream adjustments, such as channel enlargement, often necessitate management or restoration regardless of whether the channel has finished adjusting to its new flow regime or not (Booth, 1990; National Research Council, 1992; Kondolf et al., 2002). This is usually caused by channel enlargement exposing pipes or undercutting roads and other structures adjacent to the stream and excessive sedimentation damaging habitat and property downstream. In these cases, restoration based on natural equilibrium from a reference reach can reduce the time needed for the degraded reach to achieve a new urban equilibrium (Rosgen, 2001).

2.4 Post-restoration Project Evaluation

Post-restoration project evaluation, the final step of the restoration plan, is crucial in verifying achievement of goals and providing project validation (National Research Council, 1992; Kondolf, 1995; Downs and Kondolf, 2002; Rosgen, 2004; Bernhardt et al., 2005). Both government officials and the public are partners in wanting this knowledge (Kondolf, 1995; Tunstall et al., 2000). One method of assessment is the post-project appraisal (PPA), which is an "…evaluation of the effectiveness of a restoration project based on systematic data collection" (Downs and Kondolf, 2002, p. 477). Rosgen's (2001) stream stability assessment methodology also can be used to monitor restoration projects. Monitoring should include both qualitative and quantitative assessments of physical and biological stream characteristics, as well as social perceptions (Kondolf and Micheli, 1995; Downs and Kondolf, 2002; Guilfoyle and Fischer, 2006). Assessments should be conducted on regular intervals (seasonally, annually or based on bankfull events) for at least a decade after restoration is completed to capture hydrological and ecological variations (Cairns, 1990; Kondolf, 1995; Kondolf and Micheli, 1995; Smith, 1997; Shields et al., 1998; Downs and Kondolf, 2002; Lake, 2005; Guilfoyle and Fischer, 2006). Lack of resources may prevent long-term, repetitive monitoring and allow for only one post-project evaluation (Downs and Kondolf, 2002). This type of evaluation, termed a "one-shot PPA" by Downs and Kondolf (2002, p205), is most beneficial for determining design compliance and short-term goal achievement, especially when pre-project data are available.

Data gathered from post-project evaluation can be compared to either pre-restoration data or data collected from a natural reference site to determine whether restoration improved the stream condition (Kondolf and Micheli, 1995; Downs and Kondolf, 2002; Palmer et al., 2005). Post-project data also can contribute to adaptive management. Brookes and others (2005, p. 205) defined adaptive management as the "…systematic process for continuous improvement of management policies and practices, by learning from the outcomes of ongoing and/or completed projects".

Results from several projects from around the world could be used to improve future restoration projects through adaptive management [e.g., the United Kingdom (Brookes et al., 2005), the Netherlands (Cals et al., 1998), Sweden, and New Zealand (Suren and McMurtrie, 2005; Suren et al., 2005)]. For example, in Mississippi, stream rehabilitation resulted in an increase in pool habitat as well as increases in fish density and biomass (Shields et al., 1998). Fish biomass also increased in streams in Virginia where log dams and boulders were used to create pools (Maughan and Nelson, 1980). Tunstall and others (2000) discovered from surveys and interviews of residents and river managers in the UK that the public greatly valued the restored rivers and preferred to be consulted and informed during the restoration process.

Despite the benefits and increasing application of adaptive management, a majority of urban stream restoration projects, especially in the United States, are not being evaluated and/or results have not been disseminated (Middleton, 2001; Davis et al., 2003; Bernhardt et al., 2005). The main reason cited for not performing this last step of the restoration plan is the lack of funding, especially for long-term monitoring (Kondolf and Micheli, 1995; Bernhardt et al., 2005). Nonetheless, knowledge of restoration results minimizes the possibility of repeating failures in the future, thus improving restoration effectiveness and reducing future costs (Downs and Kondolf, 2002; Johnson et al., 2002).

3. GEOMORPHOLOGY ARTICLE

3.1 Overview

Rapid urban growth of Austin, Texas, has resulted in significant alteration of the surface characteristics of the Colorado River Watershed. These changes have increased the runoff and accelerated erosion of the banks of stream channels. To minimize the threat of stream erosion to real estate and infrastructure, the City of Austin began restoring unstable channel reaches through the placement of rock armor on the banks, construction of rock grade controls, and planting of riparian vegetation. Since the late 1990s, approximately thirty channel reaches have been restored in the Austin area. Considerable discussion is taking place regarding the true impact of restoration on streams. Few studies have attempted to conduct post-project evaluation to assess the impact of restoration efforts. Because it has been several years since steps were taken to stabilize these streams, a sufficient time period for stabilization to occur has passed. Thus, we believe these projects now can be assessed for the temporal impact of restoration on these streams.

We studied the restored and present "natural" reaches of two of these streams. The "natural" reaches served as ergodic surrogates for temporal channel development of the restored reaches. Although Walter and Merrits (2008) argue that "natural" streams no longer exist, we think it is important to understand current "natural" conditions to use as the basis for stream restoration planning and monitoring. We used Rosgen's (2001) methodology of channel stability assessment and repeat ground photography (Graf, 1985) to evaluate the stability of Waller Creek and Tannehill Branch. Variables of channel morphology analyzed included riparian vegetation cover, vertical stability, scour/deposition potential, and bed sediment composition. From our analysis, restoration enlarged stream channels, decreased bank height ratios and reduced flood prone width. Bed sediment analysis revealed that pools contain a higher percentage of fines whereas riffles sediments are coarser in restored reaches than pre-restoration reaches. Visual examination of ground photographs and the Pfankuch channel stability evaluation indicate that restoration increased vegetative cover and deposition. Thus, restoration efforts worked on these two streams. Data from the assessments of stream channel stability provide the basis upon which longer-term monitoring and evaluation can be conducted. Knowledge gained from long-term monitoring can be used to improve the effectiveness of the current and future restoration projects in Texas and elsewhere.

3.2 Introduction

Urbanization alters river channels. Researchers, beginning with Leopold and Wolman in the late 1960s, have studied the cause, magnitude, duration, and location of these alterations (Chin and Gregory 2005). Appropriately, this knowledge has been increasingly applied to stream restoration projects during the past ten years (Riley 1998). As restoration can be a vital step in reducing and reversing the negative impacts of anthropogenic activities (Berger, 1990; Lassettre, 1997), the practice of restoring streams becomes significant in heavily populated areas such as Texas, where 297 cities are predicted to double in population over the next fifty years (TWDB, 2006).

Austin, Texas, in particular, has attempted to restore many stream reaches degraded by urban expansion associated with population growth (City of Austin, 1995a). The City of Austin used fluvial geomorphological principles to design the restoration of degraded urban streams (Kondolf et al., 2002). Considerable discussion is taking place regarding the true impact of restoration on streams. However, few studies have investigated what occurs post-restoration (Kondolf and Micheli, 1995), and whether these urban streams are able to achieve a more stable state (Booth, 2005). Thus, one has to ask: How effective have stream restoration efforts been at improving stream stability in the Colorado River watershed in Austin, Texas?

The overall objective of this research was to evaluate the effectiveness of restoration practices on restored reaches of urban stream channels in Austin. To achieve this objective, we evaluated the stability of the stream channels using Rosgen's methodology of channel stability assessment (2001) and repeat ground photography based on methodology by Graf (1985). We hypothesized that the restoration practices employed in Austin were effective at restoring stream stability, as they were based on sound, geomorphic principles.

3.3 Setting the Stage

Austin is located in Travis County in central Texas (Figure 1). The city is situated on the boundary between the Blackland Prairie and Edwards Plateau ecological regions. This area of Texas has a subtropical-subhumid climate with annual temperatures ranging from 14^{o}C to 26^{o}C and average precipitation of 810 mm (Larkin and Bomar, 1983). The geology of the area is predominantly Cretaceous chalks overlain by fluvial terrace sediments and Quaternary alluvium (Proctor et al., 1974). Elevations range from 130 m near the Colorado River to 200 m at the tributary headwaters (Proctor et al., 1974). This study evaluates two tributaries of the Colorado River, Tannehill Branch and Waller Creek, both of which flow over limestone and have perennial flows.

Austin developed along the Colorado River, which flows northwest to southeast through the city (Figure 1). The Colorado River and its tributaries have dissected the Blackland Prairie and Edwards Plateau, creating steep-sloped river valleys that drain the Austin area and several other nearby cities (Gould, 1975; Marsh and Marsh, 1995). This physiographic feature, along with intense precipitation that occurs in this region, has led to major flooding and the nickname of “Flash Flood Alley” (City of Austin, 1995c, [http://www.ci.austin.tx.us/watershed/floodhistory.htm]).

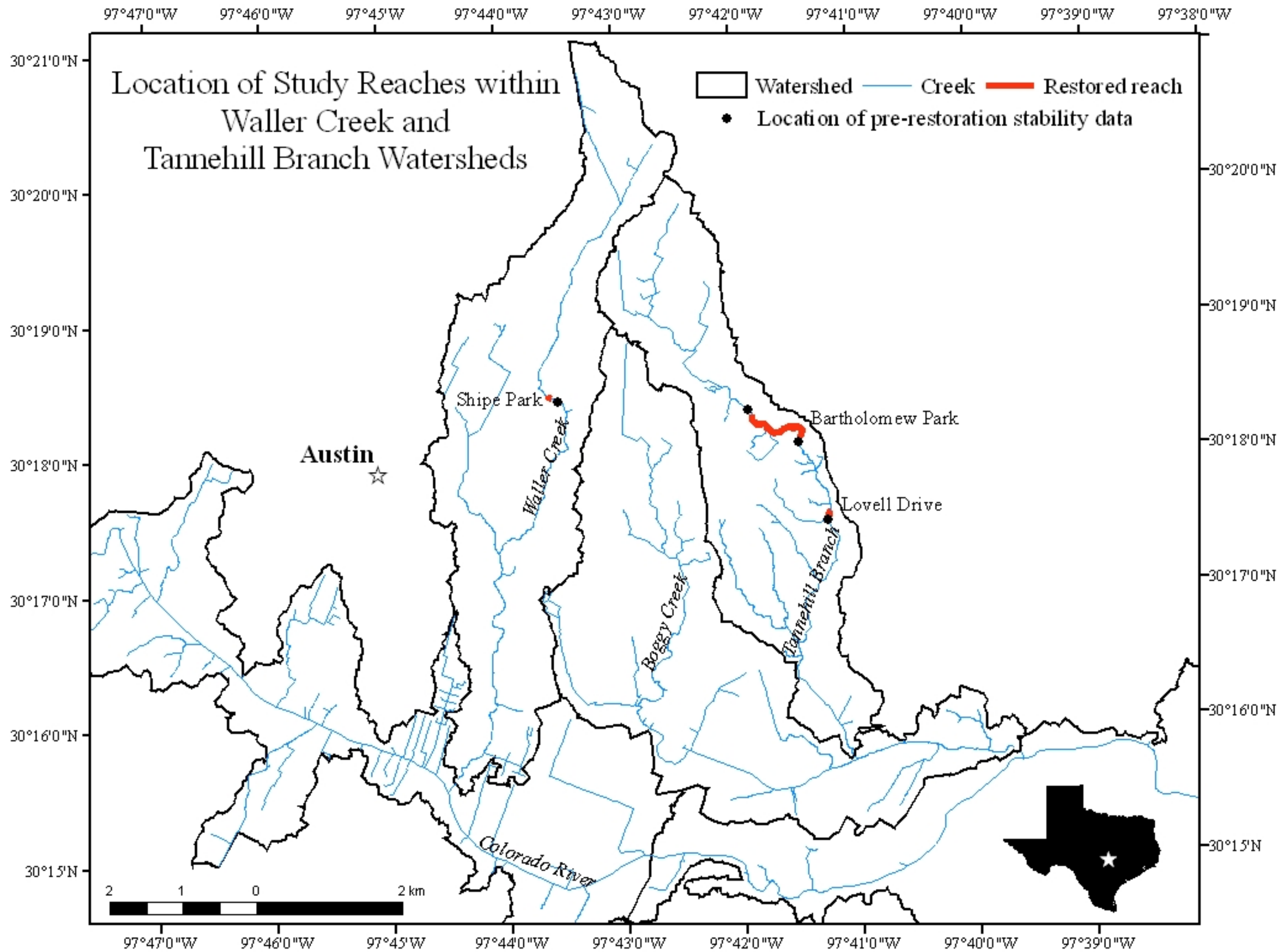

Figure 1. Location of study sites within the Tannehill Branch and Waller Creek watersheds.

Rapid urban development over the past few decades has increased stormwater runoff, leading to greater erosion within stream channels (refer to Figure 23 on page 57; City of Austin, 1995b; Marsh and Marsh, 1995). By 1995, the City of Austin Watershed Protection Development Review had identified 947 cases of localized stream erosion, with 160 channel reaches classified as unstable (City of Austin, 1995a).

To minimize the threat of stream erosion to property (Figure 2), the City of Austin began restoring channel reaches using bank stabilization (Figure 3), constructing limestone rock grade controls (Figure 4), and planting of riparian vegetation (Figure 5). Since the late 1990s, approximately thirty channel reaches have restoration features established (City of Austin, 1995a). A majority of these projects, however, were limited to bank stabilization because of space constraints typical of urban stream environments. Of the remaining projects in which more extensive restoration techniques were applied, two projects are in city parks and one is adjacent to a public golf course. The following sections describe these three projects.

Figure 2. Tannehill Branch immediately upstream of Lovell Drive restoration site, March 2006.

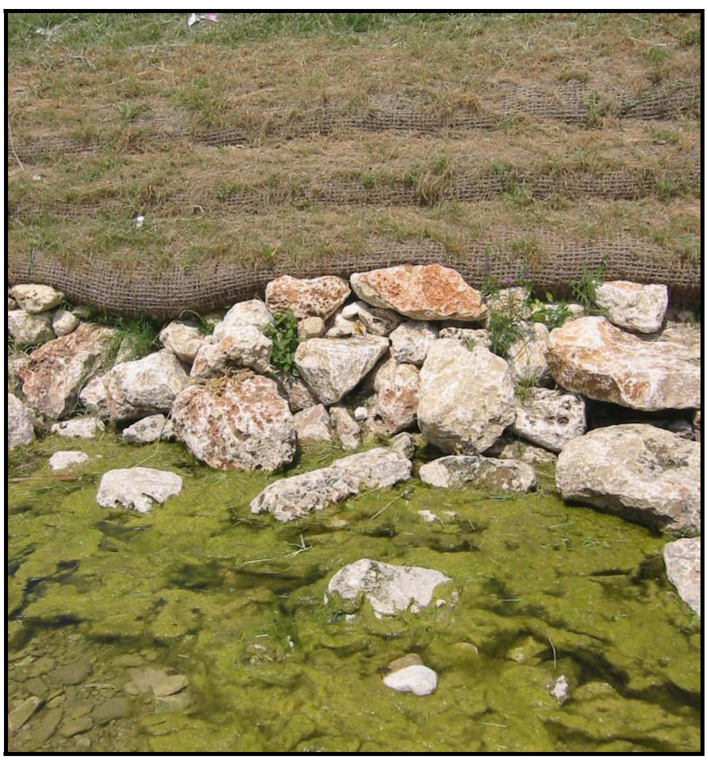

Figure 3. Example of bank stabilization on Tannehill Branch in Bartholomew Park using limestone rock and erosion control netting, May 2007.

Figure 4. Example of limestone grade control structure at the Lovell Drive restoration project on Tannehill Branch, July 2007.

Figure 5. Native trees, shrubs, and grasses planted on the restored banks of Waller Creek in Shipe Park, July 2007.

3.3.1 Tannehill Branch – Bartholomew Park

Two of these extensively restored sites were located on the Tannehill Branch of Boggy Creek in northeast Austin (Figure 1). The drainage area of this watershed is ~ 1,000 ha, and the dominant land use throughout the watershed is residential (figure on page 58; City of Austin, 2001a). The first restored site is located in the center of the Tannehill watershed in Bartholomew Park. Intense runoff from residential areas had resulted in a channel that was unstable and highly eroded (Figure 6). In 2001, the City of Austin restored the channel in the eastern section of the park. In 2006, restoration of the stream in the western portion of the park was completed, for a total restored length of ~ 820 m. Restoration involved reconstructing the channel using rock gabions and limestone boulders to armor banks and to provide grade control within the channel, as well as planting of native vegetation (Figure 7; City of Austin, 2001b). Erosion control blankets were installed underneath limestone boulders to provide toe protection and various types of erosion control netting were used to stabilize the banks until vegetation became established (Figure 3).

Figure 6. Tannehill Branch in Bartholomew Park, next to baseball fields, before restoration in 2003 (Courtesy M. Rotar).

Figure 7. Tannehill Branch in Bartholomew Park, next to baseball fields, after restoration in 2007.

3.3.2 Tannehill Branch – Lovell Drive

The second restoration site on Tannehill Branch is along the eastern boundary of Morris Williams Golf Course on Lovell Drive (Figure 1), ~ 1 km downstream of Bartholomew Park. A portion of a fairway on the golf course was damaged by erosion along the outside of a meander bend (Figure 8). In 2005, ~ 100 m of the stream was restored similar to the restoration site in Bartholomew Park. This golf course reach was stabilized with limestone rock armor along the outside of the meander bend, construction of a pool-riffle system, and planting of native vegetation (Figure 9; City of Austin, 2001b). Fabric encapsulated soil lifts were used to stabilize the banks above the limestone rocks until vegetation became established (Figure 10).

Figure 8. Tannehill Branch at Lovell Drive before restoration in 2005 (City of Austin, 2001a).


Figure 9 Tannehill Branch at Lovell Drive after restoration in 2007.


Figure 10. Fabric encapsulated soil lift with rock toe protection on banks of Tannehill Branch downstream of Lovell Drive.

3.3.3 Waller Creek – Shipe Park

The third restored site is located in the central part of the Waller Creek watershed in Shipe Park (Figure 1). The Waller Creek watershed is a highly urbanized watershed in Austin, with both the University of Texas and the State Capitol building situated within this 1,600 ha watershed (refer to Figure 23 on page 57;City of Austin, 2001a). In the late 1800s, Shipe Park was part of "Lake Ney", a private lake created by a dam (refer to Figure C-35 on page 103) on Waller Creek that is a national historic site (Fisher, 2001). Severe erosion enlarged the channel to the point that park facilities were being undercut (Figure 11; City of Austin, 2001b). In 1998, both rock armor and native vegetation were placed to stabilize ~ 95 m of the stream bank and a pool-riffle system was constructed to protect the stream bed (Figure 12; City of Austin, 2001b). Erosion blankets were installed to stabilize the banks until vegetation became established (Figure 13).

Figure 11. Waller Creek in Shipe Park before restoration c.a.1995 (City of Austin, 2001a).

Figure 12. Waller Creek in Shipe Park after restoration in July 2007.

Figure 13. Erosion control blanket used to stabilize the banks of Waller Creek in Shipe Park, March 2007.

3.4 Methods

To address the research question of what the impact of restoration efforts are on the stability of these streams, data describing the geomorphological variables influencing stability were collected from the restored reaches following Rosgen's methodology (2001) and compared to pre-restoration geomorphological data from topographic surveys conducted by the City of Austin in 1995, 2000 and 2003. Values from channel stability evaluations (Pfankuch, 1975) conducted in the present study at the restored reaches were compared to pre-restoration values provided by the City of Austin from reaches downstream to the restored reach. The distribution of particle sizes from bed sediment of the restored reaches was analyzed. Repeat ground photography was used to study visual evidence of changes in stability of the restored channel reaches.

The present study used the following data provided by the City of Austin Watershed Protection Development Review: photographs of the reaches to be restored; topographic maps constructed from pre-restoration surveys; restoration designs for all the restored reaches; bed sediment data in the form of a pebble count for the Bartholomew Park reach and a particle size analysis for the Lovell Drive stream reach; Pfankuch channel stability evaluations (Pfankuch, 1975; Table A-1) from reference reaches (upstream and downstream of Bartholomew Park, downstream of Lovell Drive, and downstream of Shipe Park; Figure 1). Post-restoration data collected by the City of Austin include channel stability evaluations for the previously mentioned reference reaches and photographs of the restored reaches.

Rosgen's channel stability assessment (2001) involved analyzing the post-restoration channel hydraulics and stability within each restored reach. A minimum of two cross-sections within pools and two cross-sections within riffles from each restored reach were measured to represent variability in channel morphology. Channel morphological data at each cross-section were obtained with an automatic level and tape. Median sediment size was determined for bed sediments collected at the thalweg of each pool using a hand-core sediment sampler and from riffles using the Wolman pebble count method (Wolman, 1954). These data were used to analyze changes in the configuration of the bed.

Pre- and post-restoration cross-sectional area, hydraulic radius, and mean/bankfull depth were determined using a planimeter and ruler. These data, along with bed and bankfull water surface slope calculated from a topographic map, were used to calculate pre- and post-restoration vertical stability (Rosgen, 2001), entrenchment ratio (Rosgen, 1994), sinuosity, width/depth ratio following nomenclature of Rosgen, (2001), velocity (Equation 1), bankfull discharge (Equation 2), peak flow (Equation 3), and bankfull shear stress (Gordon et al., 2004; Equation 5) in Microsoft Excel®. All of the channel hydraulic data generated using Microsoft Excel® was entered into a statistical package, such as SPSS®. A paired *t*-test was used to determine whether the restored stream reaches are significantly different than the same stream reach before restoration.

For the velocity calculation, Manning's equation was used with a roughness coefficient of 0.05 which was representative of the roughness of the streambed and banks (Gordon et al., 2004):

$$v = k\frac{R^{\frac{2}{3}}s^{\frac{1}{2}}}{n} \tag{1}$$

Where: v = mean velocity (m sec^{-1}), k=1.00 (m), R=hydraulic radius (m), s=slope, and n=Manning's roughness coefficient.

The velocity calculated in Equation 1 was used to determine the bankfull discharge from each cross-section and each reach:

$$Q = AV \tag{2}$$

Where: Q =stream discharge (m^3 sec^{-1}), A=cross-sectional area (m^2), and V=mean velocity (m sec^{-1}).

The peak flow was estimated to determine the impact of land use changes in the watershed on stream discharge:

$$q = 1.008CiA \tag{3}$$

Where: q=peak flow (ft^3 sec^{-1}), C=runoff coefficient based on slope, soil group and land use, *i*=average rainfall intensity (in h^{-1}), and A=drainage area (acres). The peak flow in Equation 3 was converted to m^3 sec^{-1}. A 25-yr storm frequency with a duration based on the Kirpich equation (1940; Equation 4) was used to calculate the average rainfall intensity in Equation 3:

$$t_c = 0.00778L^{0.77}S^{-0.385} \tag{4}$$

Where: t_c=time of concentration (min), L=maximum hydraulic length (ft), and S=mean slope along hydraulic length.

Shear stress provides the force to transport sediment. Bankfull shear stress was calculated to determine the force applied to the bed and banks of the restored reaches and for use in Equation 6 to calculate the sediment size entrained at bankfull flows:

$$\tau_{bkf} = \rho g R S \tag{5}$$

Where: τ_{bkf}=shear stress (N m^{-2}), ρ=water density=1000 (kg m^{-3}), g=gravitational acceleration=9.807 (m s^{-2}), R=hydraulic radius (m), and S= slope.

Particle size distributions were calculated from the pebble count data from riffles and the results of the sieve analysis of bed sediments from pools (Kondolf et al., 2002; Gordon et al., 1992). Median diameter size of fine and coarse sediment, determined from the 2007 particle size distributions, was compared to pre-restoration sediment data and the particle size calculated from Shield's equation (Equation 6; Gordon et al., 2004) to predict the channel condition at which entrainment of sediment occurs:

$$d = \frac{\tau_{bkf}}{\theta_c g(\rho_s - \rho)} \tag{6}$$

Where: d=representative particle size (m), τ_{bkf}=shear stress (N m^{-2}), θ_c=Shield's paramter≈0.07, ρ_s=particle density=2650 (kg m^{-3}), ρ=water density=1000 (kg m^{-3}), and g=gravitational acceleration=9.807 (m s^{-2}).

Channel stability parameters in the restored reaches and downstream reaches were evaluated based on the Pfankuch stability evaluation method (1975; Table A-1). The channel characteristics evaluated include percent of vegetation on banks, bank rock content, bed sediment size distribution, brightness, percent clinging aquatic vegetation, consolidation of particles, cutting, days after storm, debris jam potential, degree of entrenchment, deposition, landform slope, mass wasting, obstructions and deflectors, rock angularity, scouring and deposition. This approach for evaluating channel stability has been used by the City of Austin for several years, as well as in other aquatic habitat studies (e.g., Townsend et al., 1997; Duncan et al., 1999).

Photographs from different locations and perspectives within the restored reach, as well as from unrestored reference reaches on the same stream, were acquired following the steps described by Graf (1985) but modified for a digital camera. As the pre-restoration photographs represented the condition of the channel during the spring/summer months, a majority of the post-restoration photographs were taken during the same time of year to minimize seasonal influence. In addition, post-restoration photographs from the fall/winter months were used for this analysis as the minimal vegetation during these months allowed for a more thorough visual examination of channel morphology. The photographs from this study were reconfigured to achieve a similar scale as those photographs from the City of Austin. Repeat ground photography is a simple, inexpensive, and quick method to document changes in channel condition over time (Rasmussen and Voth, 2001). Photographs of present conditions, as well as those taken by the City of Austin before restoration, were visually compared and analyzed. Any changes within the stream channel or in the riparian zone were measured and documented.

A geographic information system (GIS) was used to analyze land use shape files from 1990, 1995, and 2003 downloaded from the City of Austin Communication and Technology Management Department website. Any significant changes of land use in the watershed upstream of the restored reaches were noted. GIS was additionally used to calculate the sub-watershed area and calibrate field measured elevation and slope using USGS topographic maps and digital elevation models (DEM) (Texas Natural Resources Information System, http://www.tnris.state.tx.us/).

3.5. Results

3.5.1 Channel Hydraulics of Tannehill Branch – Bartholomew Park

Analysis of morphological data shown in Appendix B and summarized in Table 1 revealed that restoration practices on Tannehill Branch in Bartholomew Park increased reach width, depth and area. Restoration increased pool width from 10.29 m to 12.33 m, which is slightly less than the design goal of 13.43 m. The width of design and post-restoration riffles was 13.69 m and 13.25, respectively, whereas the pre-restoration width was ~ 40% narrower at 7.79 m. Pool and riffle depth increased by ~ 0.01 m to 1.19 m and 1.12 m, respectively, after restoration, which is similar to the restoration design depths of 1.03 m and 1.18 m. Riffle width:depth ratio met the restoration design goal of a 50% increase, from 7.72 m to 11.86 m, whereas restored pool width:depth ratio (10.32 m) remained the same as the pre-restored condition (10.48 m).

Table 1 shows that the flow velocity estimated from Manning's equation (Equation 1) was ~2 m sec^{-1} for both the pre-restored and the current restored condition. However, the increase in channel area, particularly in pools, increased the overall discharge by 25%, from 17.66 m^3 sec^{-1} to 21.96 m^3 sec^{-1}. Restoration reduced bankfull shear stress from 54.54 N m^{-2} to 44.42 N m^{-2} therefore the frictional force in the channel was less than that before restoration and the restoration design. This reduction of stress on the bed and banks also reduced the particle size of sediment capable of entrainment in this reach of Tannehill Branch from ~50 mm to ~40mm.

The stability rating of the bank height ratio (Rosgen, 2001) before restoration in Bartholomew Park was unstable, which suggests a high risk of degradation. The post-restoration channel has a lower ratio, which is equivalent to a moderately unstable rating or a moderate risk of erosion (Rosgen, 2001). Restoration reduced the flood-prone width from 30 m to 14 m, which lowered the entrenchment ratio (Table 1), and resulted in a channel that is more vertically contained than before restoration.

Table 1. Channel hydraulic and morphologic data from Tannehill Branch at Bartholomew Park, 2007.

Parameter	Units	Pre-restoration	Restoration design	Post-restoration
Slope, bed	$m\ m^{-1}$	0.0067	0.0067	0.0067
Slope, bankfull	$m\ m^{-1}$	0.0091	0.0091	0.0091
Pool average width	m	10.29	13.43	12.33
Pool average depth	m	0.98	1.03	1.19
Pool w:d	--	10.48	13.06	10.32
Riffle average width	m	7.79	13.69	13.25
Riffle average depth	m	1.01	1.18	1.12
Riffle w:d	--	7.72	11.62	11.86
Reach average width	m	8.91	13.56	12.73
Reach average depth	m	1.04	1.10	1.23
Reach w:d	--	8.56	12.29	10.33
Pool hydraulic radius	m	0.80	0.90	0.82
Riffle hydraulic radius	m	0.79	1.01	0.53
Reach hydraulic radius	m	0.84	0.95	0.69
Manning's n	--	0.04	0.04	0.04
Pool velocity	$m\ sec^{-1}$	1.82	1.97	1.59
Riffle velocity	$m\ sec^{-1}$	1.76	1.90	1.78
Reach velocity	$m\ sec^{-1}$	1.74	2.05	1.34
Pool average area	m^2	11.05	13.93	17.13
Riffle average area	m^2	7.50	15.09	9.97
Reach average area	m^2	9.70	14.51	13.83
Pool bankfull discharge	$m^3\ sec^{-1}$	19.45	26.43	30.53
Riffle bankfull discharge	$m^3\ sec^{-1}$	13.07	30.93	13.33
Reach bankfull discharge	$m^3\ sec^{-1}$	17.66	28.65	21.96
Time of concentration	min	64.28	64.28	64.28
Subwatershed area	acres	1,078.00	1,078.00	1,078.00
Intensity	$mm\ hr^{-1}$	82.70	82.70	82.70
Peak flow	$m^3\ sec^{-1}$	120.86	120.86	120.86
Bankfull shear stress	$N\ m^{-2}$	54.54	61.56	44.42
Shield's parameter	--	0.07	0.07	0.07
Particle diameter	mm	48.15	54.35	39.21
Sinuosity	--	1.26	1.26	1.26
Bank height ratio	--	1.44	1.00	1.08
Entrenchment ratio	--	3.38	--	1.10

3.5.2 Channel Hydraulics of Tannehill Branch – Lovell Drive

Results differed on Tannehill Branch at Lovell Drive from the upstream reach in Bartholomew Park. Overall width decreased ~20% from 12.24 m to 10.25 m, whereas depth remained at ~1.50 m after restoration (Appendix B, Table 2). Pool width decreased from 12.20 m to 8.79 m, which is slightly narrower than the design goal of 11.35 m. The design (11.09 m) and post-restoration riffles (11.71 m) were ~15% narrower than the pre-restoration width of 13.82 m. Depth decreased by 20% in pools, from 1.23 m to 0.97 m, but riffles increased in depth from 1.94 m to 2.01 m after restoration; neither pool nor riffle depth achieved the restoration design depth of 1.09 m. Riffle and pool width:depth ratios were lower than the restoration design goal of 10.21 m and 10.38 m by 50% (5.83 m) and 15% (9.04 m), respectively.

Flow velocity estimated from Manning's equation (Equation 1) was ~2 m sec^{-1} for the pre-restored, restoration design and restored reaches. The overall bankfull discharge decreased from 35.21 m^3 sec^{-1} to 23.61 m^3 sec^{-1} as a result of a reduction in cross-sectional area in the restored reach; however, the post-restoration discharge was still higher than the discharge of 18.27 m^3 sec^{-1} predicted from the restoration design. Restoration lowered bankfull shear stress from ~70 N m^{-2} before restoration to the restoration design goal of ~60 N m^{-2}. This change in shear stress resulted in a reduction of 6.21 mm in the size particle (~10%) capable of being mobilized at bankfull flow in this study reach.

The stability rating of the bank height ratio before and after restoration was moderately unstable meaning there is a slight risk of degradation (Rosgen 2001). Similar to the restoration practices used in Bartholomew Park, the restoration of Tannehill Branch at Lovell Drive resulted in a reduction of flood-prone width, from 72.00 m to 16.32 m, which lowered the entrenchment ratio (Table 2) and resulted in a channel that is more vertically contained than before restoration.

Table 2. Channel hydraulic and morphologic data from Tannehill Branch at Lovell Drive, 2007.

Parameter	Units	Pre-restoration	Restoration design	Post-restoration
Slope, bed	$m\ m^{-1}$	0.0067	0.0067	0.0067
Slope, bankfull	$m\ m^{-1}$	0.0091	0.0091	0.0091
Pool average width	m	12.20	11.35	8.79
Pool average depth	m	1.23	1.09	0.97
Pool w:d	--	9.93	10.38	9.04
Riffle average width	m	13.82	11.09	11.71
Riffle average depth	m	1.94	1.09	2.01
Riffle w:d	--	7.12	10.21	5.83
Reach average width	m	12.24	11.22	10.25
Reach average depth	m	1.47	1.09	1.49
Reach w:d	--	8.35	10.29	6.88
Pool hydraulic radius	m	0.87	0.94	0.62
Riffle hydraulic radius	m	1.42	0.95	1.27
Reach hydraulic radius	m	1.05	0.95	0.94
Manning's n	--	0.05	0.05	0.05
Pool velocity	$m\ sec^{-1}$	1.69	1.57	1.57
Riffle velocity	$m\ sec^{-1}$	1.49	1.57	1.19
Reach velocity	$m\ sec^{-1}$	2.07	1.57	1.91
Pool average area	m^2	18.02	11.76	8.53
Riffle average area	m^2	26.43	11.47	21.50
Reach average area	m^2	20.82	11.61	15.02
Pool bankfull discharge	$m^3\ sec^{-1}$	26.79	18.49	10.18
Riffle bankfull discharge	$m^3\ sec^{-1}$	54.60	18.05	41.07
Reach bankfull discharge	$m^3\ sec^{-1}$	35.21	18.27	23.61
Time of concentration	min	83.4	83.4	83.4
Subwatershed area	acres	1400	1400	1400
Intensity	$mm\ hr^{-1}$	69.2	69.2	69.2
Peak flow	$m^3\ sec^{-1}$	79.96	79.96	79.96
Bankfull shear stress	$N\ m^{-2}$	68.19	61.21	61.15
Shield's parameter	--	0.07	0.07	0.07
Particle diameter	mm	60.20	54.03	53.99
Sinuosity	--	1.13	1.13	1.13
Bank height ratio	--	1.14	1.00	1.30
Entrenchment ratio	--	5.88	--	1.59

3.5.3 Channel Hydraulics of Waller Creek – Shipe Park

Based on analysis of morphological data in Appendix B and Table 3, restoration enlarged the channel of Waller Creek at Shipe Park. Pool widths went from 8.61 m to 9.00 m and riffle widths increased from 10.11 m to 11.53 m. Pool and riffle widths were slightly narrower than the design goal of 9.65 m and 11.66 m, respectively (Table 3). However, the depth of both pools (1.43 m) and riffles (1.35 m) were deeper than the restoration design depth of 1.32 m and 1.19 m, respectively (Table 3). Riffle and pool width:depth ratios equaled 8.54 and 6.31, respectively, both of which are lower than the restoration design goal of 9.77 and 7.32, with the restored pool width depth ratio being lower than even the pre-restoration condition.

Flow velocity estimated from Manning's equation (Equation 1) was between 2 to 2.5 m sec^{-1} for this reach of Waller Creek before and after restoration as well as for the restoration design. Overall bankfull discharge of the restored reach was ~30 m^3 sec^{-1}

which is greater than the discharge from the pre-restored condition (28.44 m^3 sec^{-1}) and the restoration design reach (28.42 m^3 sec^{-1}).

Bankfull shear stress after restoration is 61.34 N m^{-2} which is less than the shear stress before restoration (66.74 N m^{-2}) and the restoration design goal (67.55 m^{-2}). Consequently, the size of particle capable of being entrained in this restored reach of Waller Creek was lowered from 58.92 mm to 54.15 mm instead of being increased as predicted by the restoration design.

The stability rating of the bank height ratio (Rosgen 2001) before restoration was 1.44 and classified as unstable but improved to 1.02, or moderately unstable, after restoration. Similar to the restoration practices used on both Tannehill Branch reaches, restoration in Shipe Park resulted in a reduction of flood-prone width from 63.36 m to 13.73 m, which lowered the entrenchment ratio from 6.83 to 1.34 (Table 3) and resulted in a channel that is more vertically contained than before restoration.

Table 3. Channel hydraulic and morphologic data from Waller Creek in Shipe Park, 2007.

Parameter	**Units**	**Pre-restoration**	**Restoration design**	**Post-restoration**
Slope, bed	$m\ m^{-1}$	0.0066	0.0066	0.0066
Slope, bankfull	$m\ m^{-1}$	0.0096	0.0096	0.0096
Pool average width	m	8.61	9.65	9.00
Pool average depth	m	1.27	1.32	1.43
Pool w:d	--	6.75	7.32	6.31
Riffle average width	m	10.11	11.66	11.53
Riffle average depth	m	1.27	1.19	1.35
Riffle w:d	--	7.98	9.77	8.54
Reach average width	m	9.28	10.46	10.27
Reach average depth	m	1.27	1.27	1.39
Reach w:d	--	7.30	8.24	7.39
Pool hydraulic radius	m	0.98	1.08	0.92
Riffle hydraulic radius	m	1.09	0.98	0.98
Reach hydraulic radius	m	1.03	1.04	0.95
Manning's n	--	0.04	0.04	0.04
Pool velocity	$M\ sec^{-1}$	2.30	2.45	2.20
Riffle velocity	$M\ sec^{-1}$	2.46	2.30	2.29
Reach velocity	$M\ sec^{-1}$	2.37	2.39	2.24
Pool average area	m^2	10.87	11.96	12.58
Riffle average area	m^2	13.40	11.78	15.44
Reach average area	m^2	12.00	11.89	14.01
Pool bankfull discharge	$M^3\ sec^{-1}$	24.99	29.30	27.64
Riffle bankfull discharge	$M^3\ sec^{-1}$	32.96	27.09	35.29
Reach bankfull discharge	$M^3\ sec^{-1}$	28.44	28.42	31.40
Time of concentration	min	90.34	90.34	90.34
Subwatershed area	acres	1156.00	1156.00	1156.00
Intensity	$mm\ hr^{-1}$	65.40	65.40	65.40
Peak flow	$M^3\ sec^{-1}$	61.90	61.90	61.90
Bankfull shear stress	$N\ m^{-2}$	66.74	67.55	61.34
Shield's parameter	--	0.07	0.07	0.07
Particle diameter	mm	58.92	59.64	54.15
Sinuosity	--	1.02	1.02	1.02
Bank height ratio	--	1.44	1.00	1.08
Entrenchment ratio	--	6.83	--	1.34

3.5.4 Statistics

Statistical analysis of the morphological data resulted in a p-value less than or equal to $\alpha=0.05$ for the following tested pairs (Table 4): pre-restoration and the design width; pre-restoration and post-restoration width; pre-restoration and the design hydraulic radius, R; and the post-restoration and design hydraulic radius, R. These results support the research hypothesis that there is a significant difference between those pairs. For the other pairs tested, the p-value was greater than 0.05. For that reason, we failed to reject the research hypothesis that there was a difference between post-restoration and the design width; pre-restoration and the design depth; pre-restoration and post-restoration depth; post-restoration and the design depth; pre-restoration and the design area; pre-restoration and post-restoration area; post-restoration and the design area; and the pre-restoration and post-restoration hydraulic radius, R.

The p-value from the paired *t*-test of the 16 samples comparing pre-restoration to design width:depth ratios was less than or equal to $\alpha=0.05$; therefore we rejected the null hypothesis that pre-restoration and design width:depth ratios are the same (Table 5). Therefore, there is significant statistical evidence that the pre-restoration and design width:depth ratios are different. However, the paired *t*-test resulted in a p-value greater than 0.05 when comparing the pre-restoration to post-restoration and design to post-restoration width depth ratios. These results indicate there is not significant statistical evidence of a difference between the pre-restoration and post-restoration width:depth ratios or the design to post-restoration width depth ratios.

Table 4. Results of paired *t*-test of pre-restoration, design and post-restoration morphological data in SPSS.

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	prewidth - designwidth	-3.69529	5.63821	1.36747	-6.59419	-.79640	-2.702	16	.016
Pair 2	prewidth - postwidth	-2.72765	5.08098	1.23232	-5.34005	-.11525	-2.213	16	.042
Pair 3	designwidth - postwidth	.96765	3.62342	.87881	-.89535	2.83064	1.101	16	.287
Pair 4	predepth - designdepth	-.07529	.38761	.09401	-.27458	.12399	-.801	16	.435
Pair 5	predepth - postdepth	-.14294	.40003	.09702	-.34862	.06273	-1.473	16	.160
Pair 6	designdepth - postdepth	-.06765	.22351	.05421	-.18257	.04727	-1.248	16	.230
Pair 7	prearea - designarea	-2.48941	9.67399	2.34629	-7.46332	2.48449	-1.061	16	.304
Pair 8	prearea - postarea	-2.13882	8.92072	2.16359	-6.72543	2.44779	-.989	16	.338
Pair 9	designarea - postarea	.35059	5.56168	1.34890	-2.50896	3.21014	.260	16	.798
Pair 10	preR - designR	-.20353	.35119	.08518	-.38410	-.02296	-2.389	16	.030
Pair 11	preR - postR	.02294	.24874	.06033	-.10495	.15083	.380	16	.709
Pair 12	designR - postR	.22647	.26756	.06489	.08891	.36404	3.490	16	.003

Table 5. Results of paired *t*-test of pre-restoration, design and post-restoration width:depth ratio in SPSS.

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	prewd - designwd	-2.62592	4.73235	1.14776	-5.05907	-.19277	-2.288	16	.036
Pair 2	prewd - postwd	-1.76532	5.73139	1.39007	-4.71213	1.18149	-1.270	16	.222
Pair 3	designwd - postwd	.86060	3.90233	.94645	-1.14580	2.86699	.909	16	.377

3.5.5 Analysis of Bed Sediments in Tannehill Branch – Bartholomew Park

All the riffles in this reach (Figure 14) sampled before and after restoration have a similar distribution of particle sizes. Sample 6 is slightly coarser than the other riffle samples from Bartholomew Park because it was collected from the older restored section in the eastern part of the park where medium boulders (~500 mm) were used to construct riffles (Figure 15). The median sediment size for the riffles is medium gravel (Table 6). For pool bed sediment, the median diameter of sediment collected during this study ranges from 0.3 to 4.0 mm (Figure 16, Table 6). There were no pre-restoration sediment samples from pools available from this reach.

3.5.6 Analysis of Bed Sediments in Tannehill Branch – Lovell Drive

The two riffles sampled (Figure 17) at Lovell Drive are more variable than the riffles in Bartholomew Park. Riffle 2 is constructed of limestone boulders for grade control and riffle 1 consists mainly of limestone gravels (Figure 18).). The median sediment size in Pool 2 is 2.2 mm and 0.7 mm in Pool 1; however, bed sediments in both pools are finer than the pre-restoration median sediment diameter of 20 mm (Figure 19 and Table 6). There were no pre-restoration sediment samples from riffles available from this reach.

Figure 14. Sites for bed sediments sample collection and cross-section measurements in Bartholomew Park.

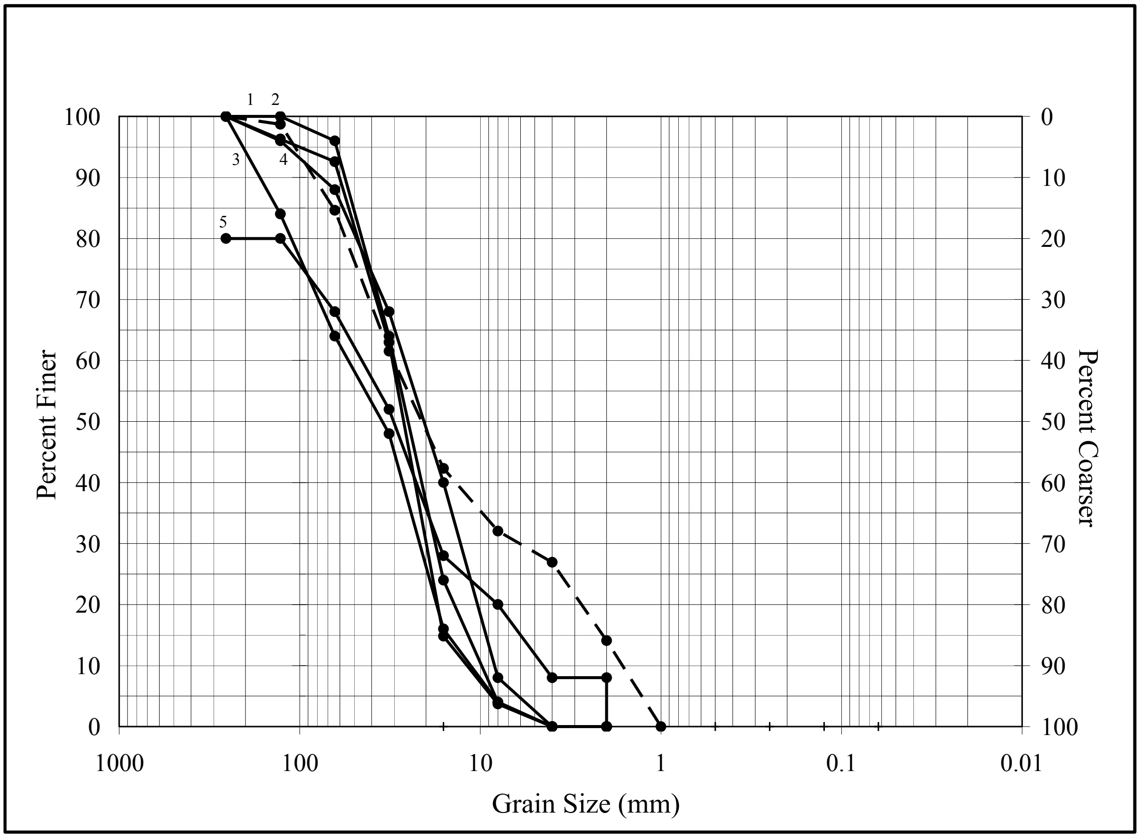

Figure 15. Cumulative frequency distribution of bed sediment in riffles, Tannehill Branch, Bartholomew Drive. The dashed line represents the sample collected before restoration by the City of Austin and the solid numbered lines represent the samples collected in 2007 from riffles 1-5 (refer to Figure 14 for location of riffles).

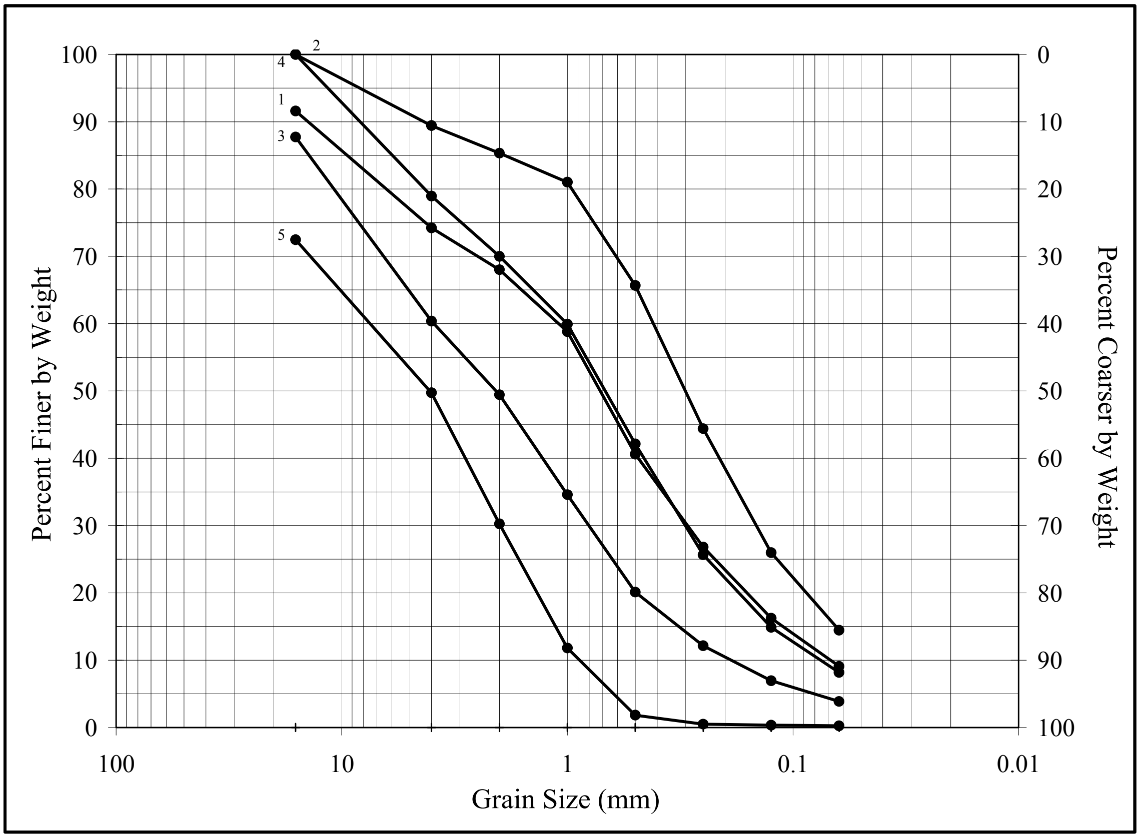

Figure 16. Cumulative frequency distribution of pool bed sediment samples, Tannehill Branch, Bartholomew Drive. The dashed line represents the sample collected before restoration by the City of Austin and the solid numbered lines represent the samples collected in 2007 from pools 1-5 (refer to Figure 14 for location of pools).

Figure 17. Sites for bed sediments sample collection and cross-section measurements at Lovell Drive.

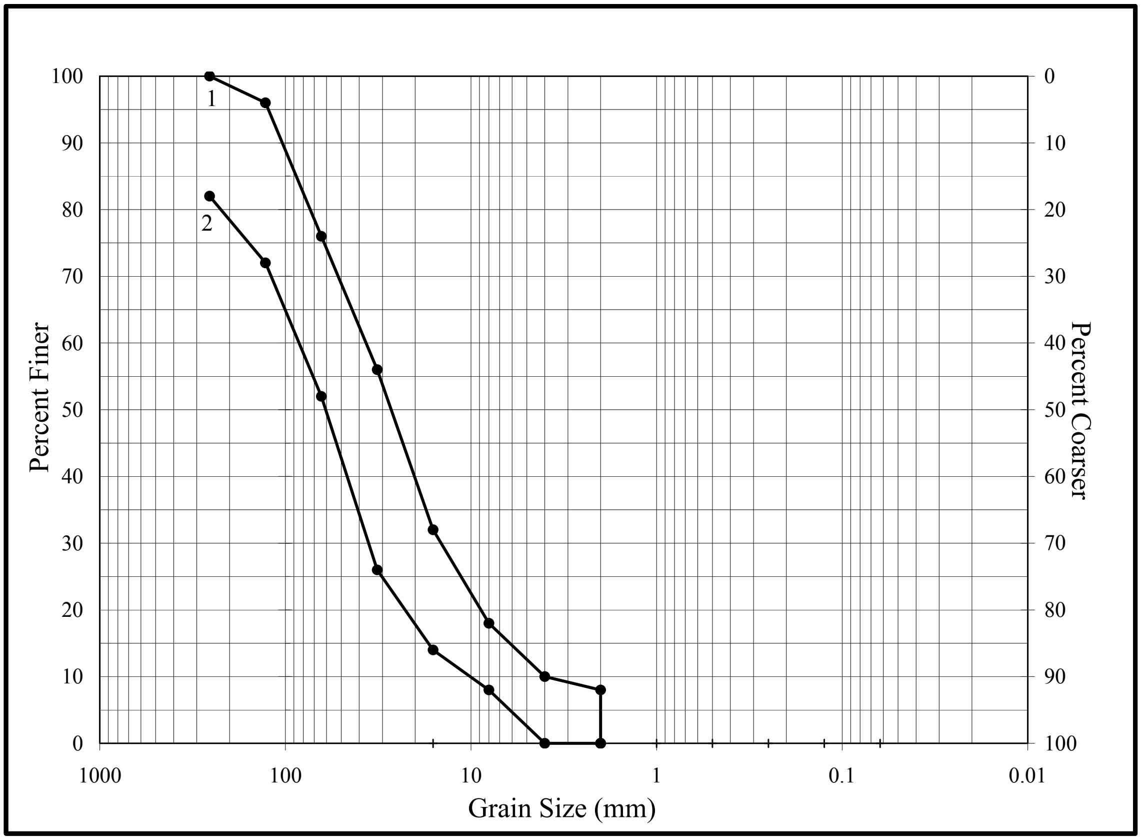

Figure 18. Cumulative frequency distribution of bed sediment in riffles, Tannehill Branch, Lovell Drive. The numbers next to the lines correspond to the riffle from which the sample was collected (Refer to Figure 17 for location of the riffles).

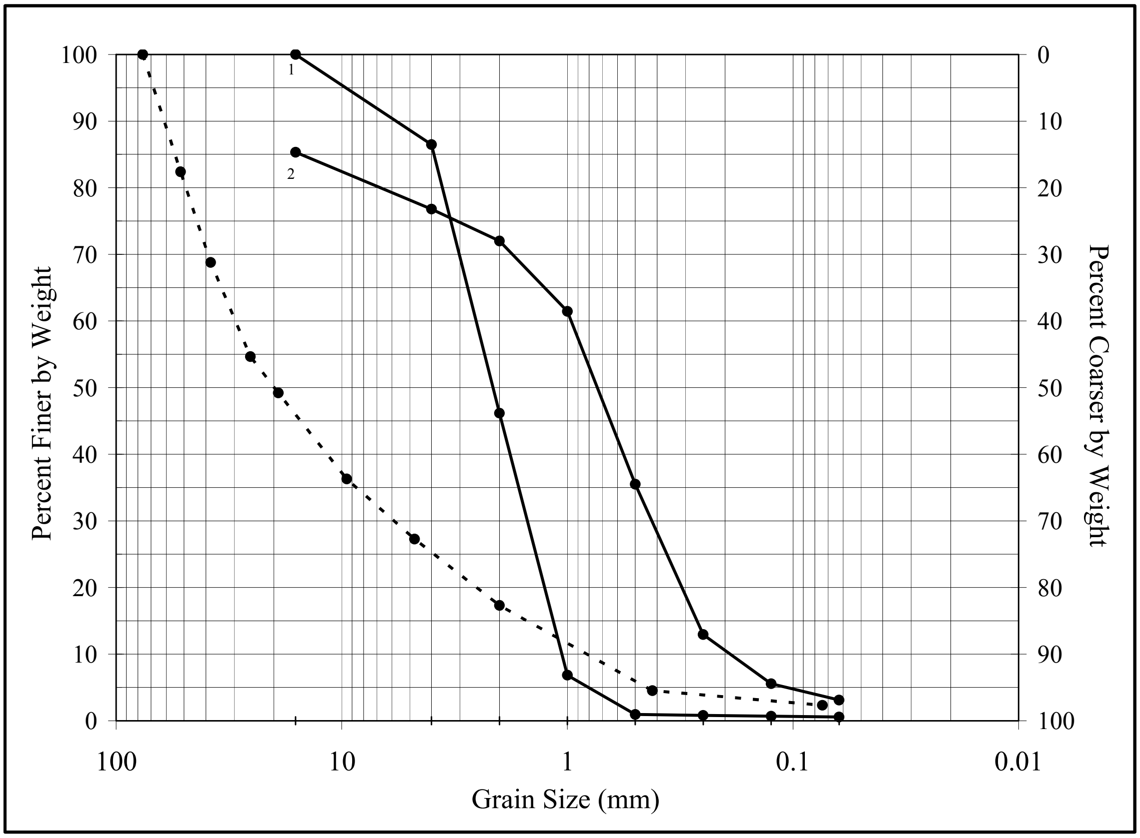

Figure 19. Cumulative frequency distribution of pool bed sediment samples, Tannehill Branch, Lovell Drive. The numbers next to the lines correspond to the pool from which the sample was collected (Refer to Figure 17 for location of the pools).

Table 6. Median diameter size of bed materials in all reaches post-restoration and for Bartholomew Park and Lovell Drive sites before restoration. Refer to Figures 14, 17 and 20 for the location of the bed sediment sample sites within each reach.

Sites	Pools (mm)	Riffles (mm)
Bartholomew 1	0.7	26.0
Bartholomew 2	0.3	25.0
Bartholomew 3	2.0	35.0
Bartholomew 4	0.7	20.0
Bartholomew 5	2.3	30.0
Bartholomew Avg.	1.2	27.2
Bartholomew-pre	—	20.0
Lovell 1	2.2	28.0
Lovell 2	0.7	60.0
Lovell Avg.	1.5	44.0
Lovell-pre	20.0	—
Waller 1	3.5	28.0
Waller 2	6.0	40.0
Waller Avg.	4.8	34.0

3.5.7 Analysis of Bed Sediments in Waller Creek – Shipe Park

The bed of Waller Creek was overall very coarse, with a majority of the particles being gravels (Figure 20 and Table 6). The sediment in the riffles ranged from fine gravel to small boulders and sediment in the pool bed consists of fine sand to small gravel (Figures 21, 22). Riffle 2 and Pool 2 are both coarser than Riffle 1 and Pool 1 (Figures 21, 22). Pre-restoration bed sediment samples were not available from this reach.

Figure 20. Sites for bed sediments sample collection and cross-section measurements in Shipe Park.

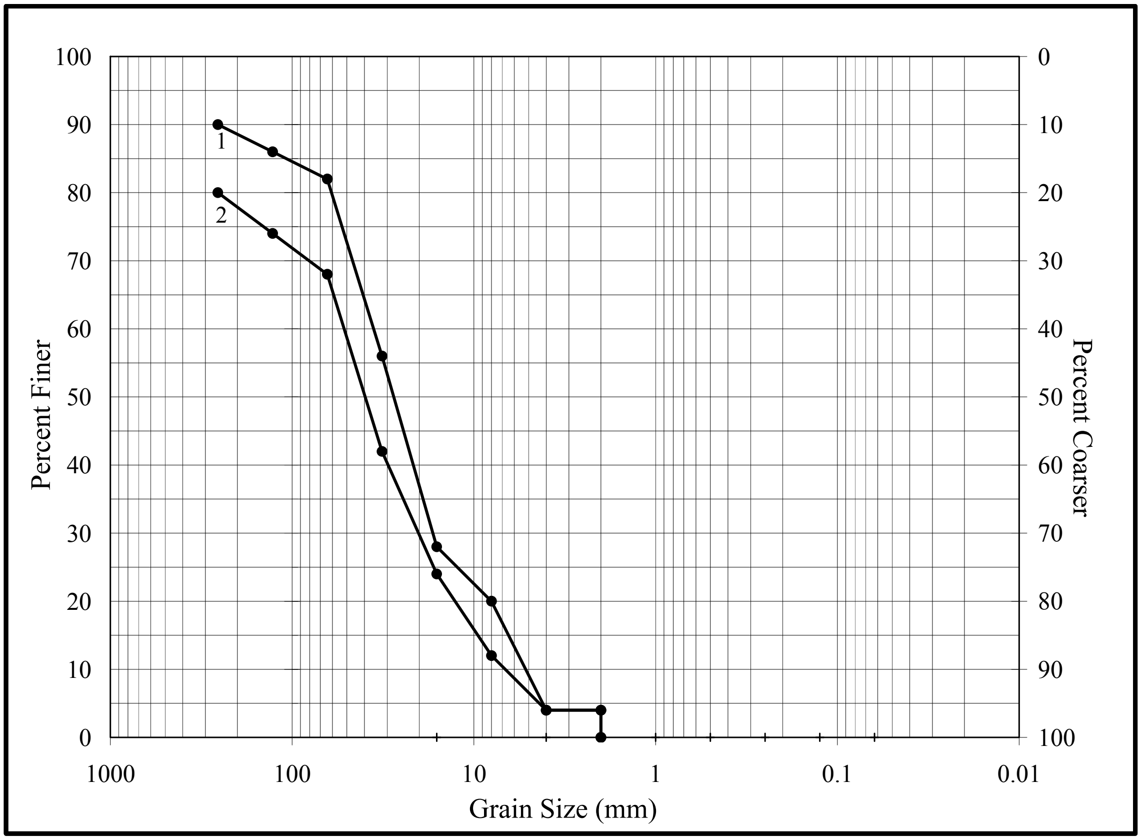

Figure 21. Cumulative frequency distribution of bed sediment in riffles, Waller Creek, Shipe Park. The numbers next to the lines correspond to the riffle from which the sample was collected (Refer to Figure 20 for location of the riffles).

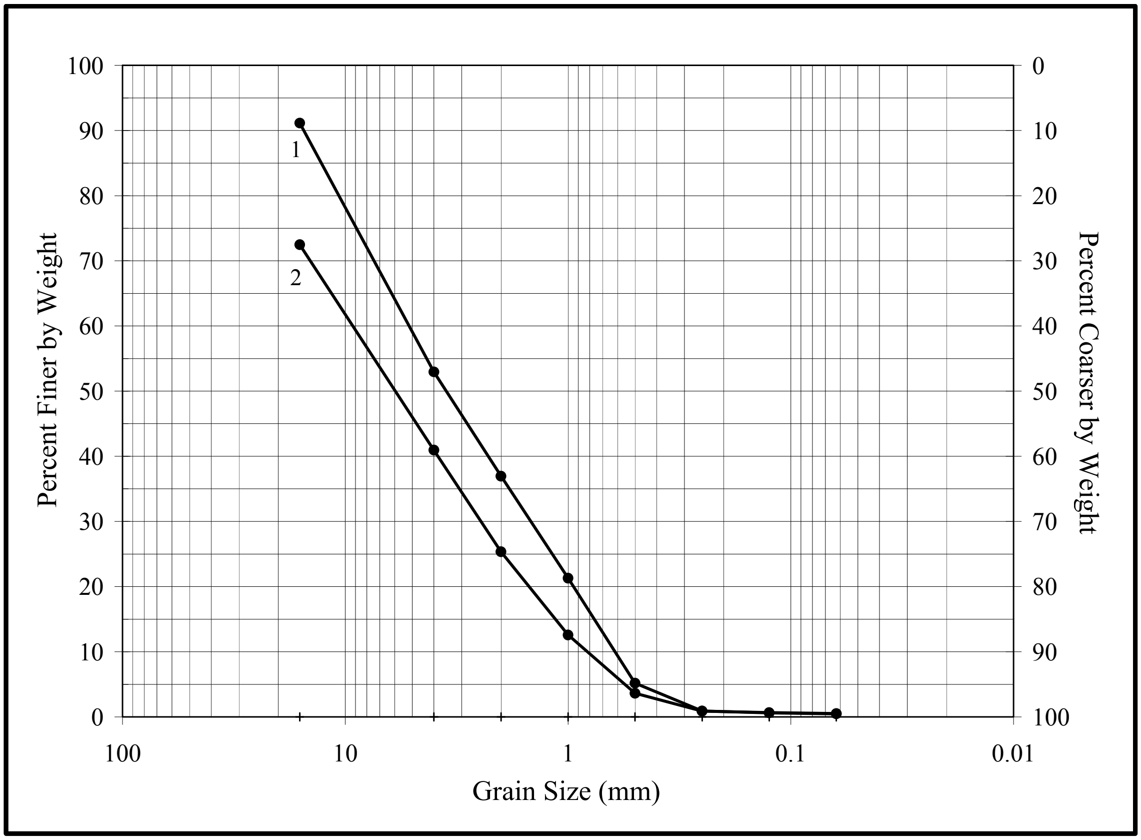

Figure 22. Cumulative frequency distribution of pool bed sediment samples, Waller Creek, Shipe Park. The numbers next to the lines correspond to the pool from which the sample was collected (Refer to Figure 20 for location of the pools).

3.5.8 Pfankuch Stability Evaluation

Tannehill Branch in Bartholomew Park before restoration had poor stability at the downstream reference reach based on the Pfankuch evaluations (1975; Table A-1) performed by the City of Austin in 1997. Evaluations by the City of Austin in 2001, 2003, and 2006 of the reference reaches downstream and upstream revealed improvement to a good stability rating, which is equivalent to the rating of the restored reach evaluated in this study (Table 7). Tannehill Branch at Lovell Drive also had a poor stability score before restoration at the downstream reference reach based on evaluations by the City of Austin in 1997, 2001, and 2003. After restoration, the downstream reference reach and the restored reach both had a fair stability rating (Table 7). The restored reach of Waller Creek in Shipe Park currently has a good stability score whereas the reference downstream reach has a fair score (Table 7). The pre-restoration score from the 1997 evaluation by the City of Austin of the reference reach indicates a more stable channel before restoration.

Table 7. Comparison of scores from Pfankuch stability evaluation (1975) conducted during this study and from prior studies completed by the City of Austin.

Site	**Score**		
	Pre-restoration[a]	*Post-restoration 1*[b]	*Post-restoration 2*[c]
Shipe Park	69	89	73
Bartholomew Park	127	67	67
Lovell Drive	126	100	88

Reach score of: <38 = Excellent, 39-76 = Good, 77-114 = Fair, 115+ = Poor

[a]Average of pre-restoration scores collected by the City of Austin between 1997-2006

[b]Average of post-restoration scores collected by the City of Austin between 1997-2006

[c]Post-restoration scores collected as part of this study; average of scores from 1 pool and 1 riffle in each reach

3.5.9 Repeat Ground Photography

Tannehill Branch in Bartholomew Park showed evidence of severe bank erosion before restoration in 2003 (i.e. Figure C-1). In addition to steep, unstable banks, this reach exhibited signs of downcutting (Figure C-13) and gully erosion (Figure C-15), all of which degraded the appearance of the park (Figure C-17) and minimized recreational opportunities (Figure C-19) in the park. Comparison of photographs from 2003 with current photographs suggests that the restoration features installed in 2006 have improved stability of the banks (i.e. Figures C-5 and C-6) and minimized downcutting (Figure C-14). Deposition has occurred in the gullies but headward erosion continues toward the road parallel to the park (51st Street, Figure C-16).

The western bank of Tannehill Branch at Lovell Drive had eroded into one of the fairways at Morris Williams Golf Course (Figure C-23). This bank was stabilized with limestone boulders that were also added to the bed to increase roughness (Figure 4). Visual analysis of 2007 photographs revealed that the boulders are intact, sand has deposited on the eastern floodplain, and vegetation has grown along the banks of the restored channel reach (Figure C-25). However, the stream does not appear to be stable. Evidence for this conclusion can be seen in the reach upstream of Lovell Drive where erosion of the steep eastern bank is undercutting property (Figure 2).

Efforts are currently underway by the City of Austin to restore this reach of Tannehill Branch using restoration methods similar to those used to restore other reaches on the this channel (Figure C-26).

Analysis of the photograph of Waller Creek in Shipe Park taken in 1995 suggests that bank failure and excess deposition occurred in the creek before restoration (Figure C-27). The only vegetation present along the channel was grasses. Comparison of this 1995 photograph to recent photographs (2007) indicate that the addition of woody vegetation and rock armoring appear to have the stabilized channel banks because there is little evidence of erosion in the ten years since restoration was completed (i.e. Figure C-30). Analysis of photographs of Waller Creek immediately upstream of Shipe Park suggests that this reach has steeper banks and less vegetation than the restored reach but appears visually stable (Figure C-33). Waller Creek immediately downstream of Shipe Park is controlled by limestone bedrock and constricted by the historic dam ~ 100 m downstream of the park (Figures 34 and 35).

3.5.10 Changes in Land Uses

The main land uses in both watersheds are residential, commercial, and transportation, each of which occupies ~30% or 780 ha of the watershed surface area. Industrial, open space, and undeveloped area account for ~10% or 260 ha of the overall land use in these watersheds. The 1990 land use map appears to have less transportation; however, all the minor streets and roadways were included in the land use analysis by the City of Austin until 1995 (Figure 23). Since 1990, the only significant change in land use was in the Tannehill Branch watershed where the site of the old airport (center of the watershed) is now considered undeveloped property. Field observation revealed that a majority of this property is currently impervious; however, future development could include the construction of streets and ditches that would channelize and expedite the movement of runoff to the stream channel. Future observations will reveal the impact of developing this property on the hydrology of the watershed and the restored stream reaches.

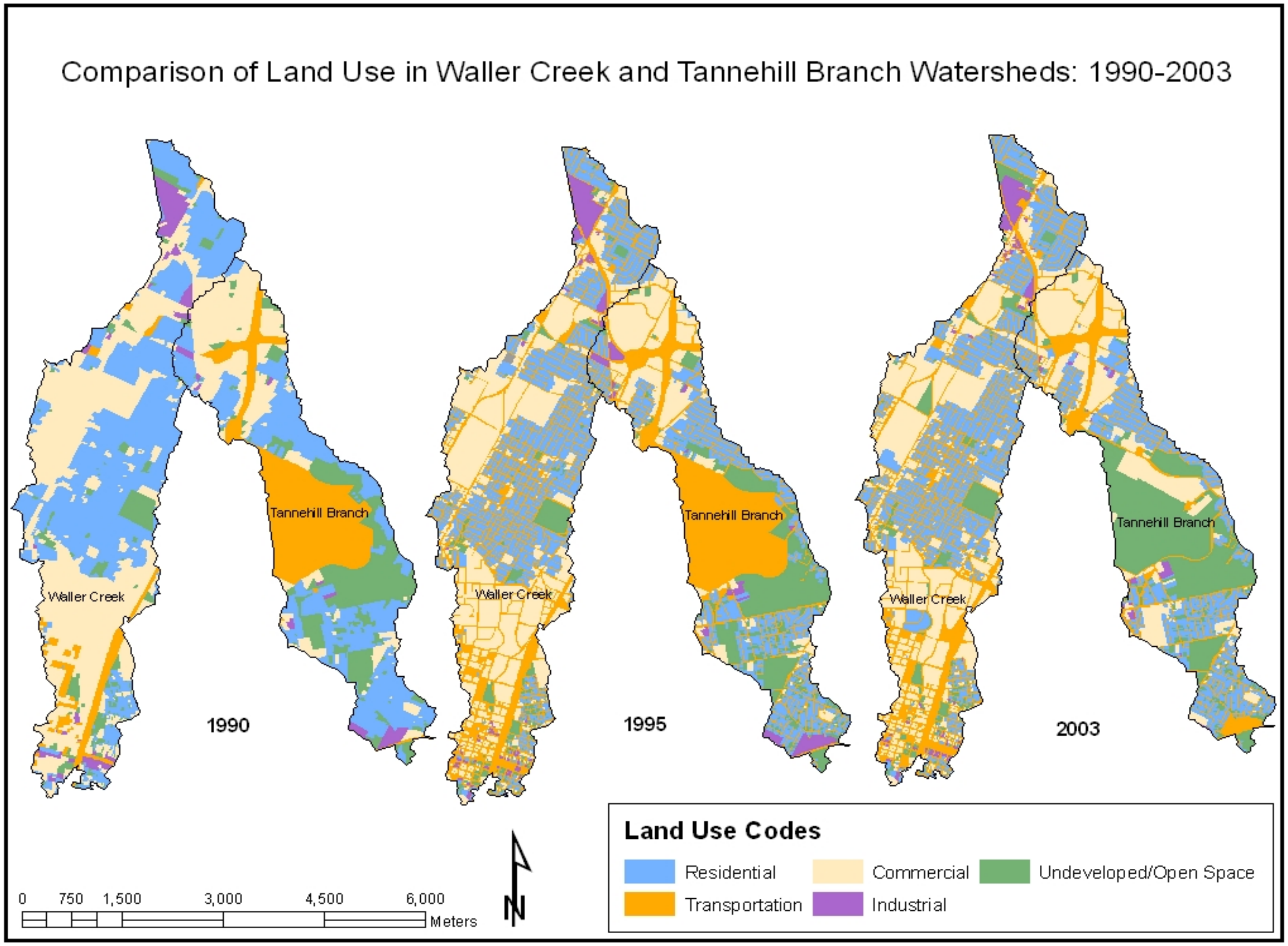

Figure 23. Land use in the two study watersheds in 1990, 1995, and 2003 (City of Austin, 2007).

3.6 Discussion

The overall objective of this study was to evaluate the effectiveness of restoration practices on restored reaches of an urban stream channel. A restoration project was considered effective if the channel was more stable than before restoration. Based on the results of this study, restoration improved the stability of the three reaches evaluated but each reach varied in magnitude of improvement.

The results from Tannehill Branch in Bartholomew Park suggest that the current reach matches the restoration design of enlarging the channel. Based on an analysis of the morphological and statistical data, the restored channel enlarged in the width direction greater than depth because bedrock minimized downward erosion. These changes in channel dimension improved stability through reducing shear stress at bankfull flow. However, there was enough shear stress at bankfull flows to entrain the median particle size of bed sediments in pools and riffles. Ground photography supports this conclusion as few depositional features are present along the channel and sediment along the stream bank has been moved downstream under the erosion control netting (Figure 24). The presence of both erosional and depositional processes suggests that the channel has achieved a state of equilibrium and stability. In addition, Pfankuch stability scores show enhanced stability along the restored reach as well as the downstream reference reach raises the question of how far downstream can “benefits” of restoration be seen?

Figure 24. Gravel moving underneath erosion control netting on stream bank of Tannehill Branch in Bartholomew Park, 2007.

The reach farther downstream on Tannehill Branch at Lovell Drive differed from that in Bartholomew Park as the restoration design reduced channel dimensions. Statistical analysis of the morphological data revealed that the width dimension of the restored channel was significantly different from the pre-restoration width; however, there was no statistical evidence of a difference in the depth dimension. The current reach surpassed the design goal and has a lower width:depth ratio. Despite this reduction in channel size, shear stress calculations indicate that bankfull flows can move all sediment currently residing in pools. Sediment transport between riffles is more variable. Based on Shield's equation and ground photography, boulders installed as part of the restoration for grade control (Riffle 2) remain intact at bankfull whereas 80% of the sediment in Riffle 1 is entrained at bankfull. However, Riffle 1 also remains intact after bankfull flows, suggesting there must be an upstream source of coarse sediment to maintain this riffle. Though the stability and frictional force of these grade control features have minimized erosion of the cut bank on this reach, they might also be the cause of excessive deposition of fine sediment in the bankfull channel (Figures 19 and 25).

Figure 25. Tannehill Branch facing downstream of Lovell Drive. Note sand bar along the left bank of the channel.

The inability of the stream to transport this sediment is part of the reason this restored reach has the lowest stability score of all the reaches in this study. Lovell Drive also had the highest bank height ratio in this study which is an indicator that the channel has a high risk of degradation (Rosgen, 2001). A lower stability rating may be the result of this reach not being in a park (which serves as a riparian buffer), like the other two reaches in this study. Reduced stability in this reach may also have been caused by the lack of stability immediately upstream of Lovell Drive (Figure 2), which is currently being restored by the City of Austin. On the other hand, this reach has the highest entrenchment ratio suggesting that the channel has not incised to the point of floodplain abandonment (Rosgen, 2001). Future monitoring efforts at Lovell Drive are needed to determine the impact of restoration on channel stability, especially once the upstream reach is restored.

The goal of the restoration design for Waller Creek at Shipe Park was to enlarge the channel. The current condition of the restored reach achieved the design width, but exceeded the design depth, resulting in a lower width:depth ratio. The post-restoration depth, however, was not significantly different from the pre-restoration or design depth as a result of bedrock controls. These channel adjustments as a result of restoration have allowed this reach to maintain stability despite a reduction in stability in the downstream reach based on the Pfankuch evaluation. It can be assumed that the reach in Shipe Park also would have had a high Pfankuch score (which translates to low channel stability) like the downstream reach, if restoration had not improved stability.

A decrease in bank height ratio to less than 1.3 indicates a reduction in risk of degradation (Rosgen, 2001) and provides additional evidence of increased stability in Bartholomew and Shipe Parks. This result is additionally supported by the analysis of ground photographs. The question remains, though, of how long will these two reaches remain stable, as a reduction in entrenchment ratios indicates that these reaches have abandoned their floodplains (Rosgen, 2001)? Entrenchment can decrease stability because instead of erosive energy from floods being dissipated on to a floodplain, that energy is now contained within the steep stream channel banks, resulting in increased erosion and bank failure (Rosgen, 1994). From a societal perspective, entrenchment could be considered as positive because less property is exposed to floodwaters given that the flood prone width is decreased. However, an entrenched channel can threaten property as banks erode and fail, and flood stage increases.

Overall, the results of this study indicate that the restoration practices in Austin, Texas, were effective at improving channel stability. These findings are similar to those found in a study by Brown (2000), where ~ 90% of the stream restoration practices analyzed were stable after approximately four years after construction. Like the City of Austin in our study, these practices used geomorphic principles and incorporated future channel adjustments into the design of the stream restoration practices.

The data from this assessment provide the basis upon which longer-term monitoring and evaluation can be conducted. Long-term monitoring will benefit current and future restoration projects through improving knowledge of restoration effects on geomorphological stream adjustments. These data will also aid in determination of which restoration practice, or practices, is the most effective at mitigating floods. Results from post-restoration evaluations also improve knowledge on how streams respond to urbanization in different environments (Kondolf, 1995; Kondolf, 1996, 1998; Lake, 2005). This knowledge could be used to determine how to reduce or control the impacts of future development on stream geomorphology.

4. ENGINEERING ARTICLE

4.1 Problem

The City of Austin is located along the Colorado River, which flows northwest to southeast through the city in central Texas (Figure 1). The combination of river valleys with steep side slopes and intense precipitation that occurs in this region results in major flooding and has earned Austin the nickname of "Flash Flood Alley" (City of Austin, 1995c, [http://www.ci.austin.tx.us/watershed/floodhistory.htm]). Rapid urban development during the past decade has enhanced the flashiness of these flood flows, resulting in greater erosion within stream channels (City of Austin, 1995b; Marsh and Marsh, 1995). By 1995, the City of Austin Watershed Protection Development Review had identified 947 cases of localized stream erosion, with 160 channel reaches classified as unstable; however, the specific location along the channel of these unstable reaches was not available (City of Austin, 1995a). This erosion has damaged property as well as transportation and utility infrastructure (Figure 2).

4.2 Solution

The impact of stream erosion on private property and city infrastructure needed to be addressed. Thus, the City of Austin began restoring channel reaches using natural channel design techniques (City of Austin, 1995a). The restoration process begins with a site assessment to determine channel conditions; historical and future channel adjustments; bed and bank characteristics, channel geometry; bed forms; amount of riparian vegetation cover; and the surface characteristics of the watershed. The site assessment is followed by analyses of hydrology, hydraulics, geomorphology, sediment transport and stability; the results of these analyses provide the basis for the design of the restored channel.

4.3 Design

Since the late 1990s, approximately 30 channel reaches have been restored within the Austin city limits (City of Austin, 1995a). The goal of the City of Austin was for these stream restoration projects to mimic nature in both function and appearance. Unfortunately, numerous stream restoration projects in Austin were limited to bank stabilization with rip-rap and gabions only because of space constraints of urban stream environments. Nevertheless, some projects, such as Tannehill Branch in Bartholomew Park, contain natural bank stabilization practices that are both aesthetically pleasing and ecologically beneficial.

The drainage area of Tannehill Branch watershed is ~ 1,000 ha, and the dominant land cover throughout the watershed is residential (City of Austin, 2001a). Intense runoff from residential areas had resulted in a channel that was unstable and highly eroded as it flowed through Bartholomew Park (Figure 6). In 2001, the City of Austin restored the channel in the eastern section of the park downstream of a flood control structure (Figure 26). In 2006, restoration of the stream in the western portion of the park was completed, for a total restored length of ~ 820 m. Restoration involved stabilizing the channel using a mixture of traditional and natural methods. The channel banks are stabilized with erosion control netting (Figure 3), fabric encapsulated soil lifts

(Figure 10) or staked geotextile fabric (Figure 13) planted and seeded with native vegetation. Limestone boulders used in previous bank stabilization efforts (Figure C-11) were not altered during restoration. Stabilization of the channel bed consists of limestone boulders used for toe protection (Figure 3) and grade control (Figure 4). Only one small segment (~20 m) of the channel in a tight meander bend in the older restored section of the park was stabilized using the traditional method of rock filled gabion baskets (Figure 27).

Figure 26. The flood control structure separating the western and eastern portions of the park. This photograph, taken in July 2007, faces downstream and shows the eastern portion of the park.

Figure 27. Example of traditional bank stabilization, rock filled gabions, July 2007.

4.4 Project Evaluation

To assess the impact of restoration efforts on the stability of Tannehill Branch in Bartholomew Park, geomorphological variables influencing stability, including riparian vegetation cover, vertical stability, width:depth ratio, scour/deposition potential, and bed sediment composition, were collected following Rosgen's methodology (2001). These variables were compared to pre-restoration geomorphological data from topographic surveys available from the City of Austin. Scores from channel stability evaluations (Pfankuch, 1975; Table A-1) conducted in this study at the restored reach were compared to pre-restoration scores from a reach downstream to the restored reach provided by the City of Austin. Bed sediment samples from the restored reach were analyzed to calculate the particle size distribution. Repeat ground photography also was used as supplementary evidence of changes in stability of the restored channel reach (Appendix C).

To ensure that any changes in channel stability were the result of restoration and not from alterations of the watershed surface, a geographic information system (GIS) was used to analyze land use shape files from 1990, 1995, and 2003 available from the City of Austin Communication and Technology Management Department website. Since 1990, the only significant change in land use was in the Tannehill Branch watershed where the site of the old airport (center of the watershed) is now considered undeveloped property. Field observation revealed that a majority of this property is currently impervious; however, future development could include the construction of streets and ditches that would channelize and expedite the movement of runoff to the stream channel. Future observations will reveal the impact of developing this property on the hydrology of the watershed and the restored stream reaches.

4.5 Results

Analysis of morphological data shown in Table 1 revealed that restoration practices on Tannehill Branch in Bartholomew Park increased reach width, depth and area. Restoration increased pool width from 10.29 m to 12.33 m, which is slightly less than the design goal of 13.43 m. The width of design and post-restoration riffles was 13.69 m and 13.25, respectively, whereas the pre-restoration width was ~ 40% narrower at 7.79 m. Pool and riffle depth increased by ~ 0.01 m to 1.19 m and 1.12 m respectively after restoration, which is similar to the restoration design depths of 1.03 m and 1.18 m. Riffle width:depth ratio met the restoration design goal of a 50% increase, from 7.72 m to 11.86 m, whereas restored pool width:depth ratio (10.32 m) remained the same as the pre-restored condition (10.48 m).

Table 1 shows that the flow velocity estimated from Manning's equation (Equation 1) was ~2 m sec^{-1} for both the pre-restored and the current restored condition. However, the increase in channel area, particularly in pools, increased the overall discharge by 25%, from 17.66 m^3 sec^{-1} to 21.96 m^3 sec^{-1}. Restoration reduced bankfull shear stress from 54.54 N m^{-2} to 44.42 N m^{-2} therefore the frictional force in the channel was less than that before restoration and the restoration design. This reduction of stress on the bed and banks also reduced the particle size of sediment capable of entrainment in this reach of Tannehill Branch from ~50 mm to ~40mm.

The stability rating of the bank height ratio (Rosgen, 2001) before restoration in Bartholomew Park was unstable, which suggests a high risk of degradation. The post-restoration channel has a lower ratio, which is equivalent to a moderately unstable rating or a moderate risk of erosion (Rosgen, 2001). Restoration reduced the flood-prone width from 30 m to 14 m, which lowered the entrenchment ratio (Table 1), and resulted in a channel that is more vertically contained than before restoration.

All the riffles in this reach (Figure 14) sampled before and after restoration have a similar distribution of particle sizes. Sample 6 is slightly coarser than the other riffle samples from Bartholomew Park as it was collected from the older restored section in the eastern part of the park where medium boulders (~500 mm) were used to construct riffles (Figure 15). The median sediment size for the riffles is medium gravel (Table 6). For pool bed sediment, the median diameter of sediment collected during this study ranges from 0.3 to 4.0 mm whereas the pre-restoration median diameter of sediment is 20 mm (Figure 16, Table 6).

Tannehill Branch in Bartholomew Park before restoration had poor stability with a score of 127 (Table 7) at the downstream reference reach based on the Pfankuch evaluation (1975; Table A-1). Since restoration, the reference reaches downstream and upstream improved to a good stability rating, which is equivalent to the rating of the restored reach (score of 67).

Tannehill Branch in Bartholomew Park showed evidence of severe bank erosion before restoration in 2003 (i.e. Figures C-1). In addition to steep, unstable banks, this reach exhibited signs of downcutting (Figure C-13) and gully erosion (Figure C-15), all of which degraded the appearance of the park (Figure C-17) and minimized recreational opportunities (Figure C-19) in the park. Comparison of photographs from 2003 with current photographs suggest the restoration features installed in 2006 have improved stability of the banks (i.e. Figures C-5 and C-6) and minimized downcutting (Figure C-14). Deposition has occurred in the gullies but headward erosion continues towards the road parallel to the park (51st Street, (Figure C-16).

4.6 Conclusion

The results from Tannehill Branch in Bartholomew Park suggest that the current reach matches the restoration design of enlarging the channel. The restored channel was enlarged more in the width direction because bedrock minimized channel incision. These changes in channel dimension improved stability through reducing shear stress at bankfull flow. However, there was enough shear stress at bankfull flows to entrain the median particle size of bed sediments in pools and riffles. Ground photography supports this conclusion as few depositional features are present along the channel and sediment along the stream bank has been moved downstream under the erosion control netting (Figure 24). Some deposition within the channel is occurring, because of a higher percentage of fine sediment in pools since restoration. The presence of both erosional and depositional processes suggests that the channel has achieved a state of equilibrium and stability. A decrease in bank height ratio after restoration further supports the conclusion that restoration increased channel stability of Tannehill Branch in Bartholomew Park. Continued monitoring of this project, as well as others in Austin and elsewhere, will provide the data needed to determine which restoration practices are the most effective at mitigating flood hazards in different locations.

5. SUMMARY AND CONCLUSIONS

From our analysis, restoration enlarged stream channels, decreased bank height ratios and reduced flood prone width. Bed sediment analysis revealed pools that contain a higher percentage of fines whereas riffles are coarser in restored reaches than pre-restoration reaches. Visual examination of ground photographs and the Pfankuch channel stability evaluation indicates that restoration increased vegetative cover and deposition. Thus, restoration efforts worked on these two streams.

The science of stream restoration is young and requires constant testing and fine-tuning for it to continue to evolve (Berger, 1990; Guilfoyle and Fischer, 2006). Most restoration projects have focused on the reach scale with few projects based on a catchment scale. Therefore, future studies are needed to determine the extent of reach scale restoration and whether multiple-reach scale restoration projects accumulate so that form and processes along the entire stream length are improved (Palmer et al., 2005; Palmer and Bernhardt, 2006). In addition, research should also address what type of catchment management strategy leads to the greatest improvement in the survival rate of in-stream structures.

Variations in the physical character and the degree of urbanization will produce different outcomes to similar restoration strategies; therefore, post-project evaluations need to be conducted in a variety of environments (Tunstall et al., 2000; Harris, 2002; Purcell et al., 2002). This will aid in the determination of which restoration strategy or strategies is the most effective at mitigating floods while also enhancing the aquatic ecosystem. Post-project evaluations of urban streams not only benefit the science of restoration but will also improve knowledge on how streams respond to urbanization in different environments (Kondolf, 1995; Kondolf, 1996, 1998; Lake, 2005). This knowledge could be used to determine how to reduce or control the impacts of future development on stream geomorphology and ecology.

REFERENCES

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology Evolution and Systematics, 35: 257-284.

Allen, P.M. and Narramore, R., 1985. Bedrock controls on stream channel enlargement with urbanization, north central Texas. Water Resources Bulletin, 21: 1037-1048.

Baron, J.S. Poff, N.L., Angermeier, P.L., Dahm, C.N., Gleick, P.H., et al., 2002. Meeting ecological and societal needs for freshwater. Ecological Applications, 12(5): 1247-1260.

Berger, J.J. (Editor), 1990. Environmental Restoration: Science and Strategies for Restoring the Earth. Island Press, Washington, DC.

Bernhardt, E.S., Palmer, M.S., Allan, J.D., Alexander, G., Barnas, K., et al., 2005. Synthesizing U.S. river restoration efforts. Science, 308: 636-637.

Booth, D., 1990. Stream-channel incision following drainage-basin urbanization. Water Resources Bulletin, 26(3): 407-417.

Booth, D.B., 2005. Challenges and prospects for restoring urban streams: a perspective from the Pacific Northwest of North America. Journal of North American Benthological Society, 24(3): 724-737.

Brookes, A., Chalmers, A. and Vivash, R., 2005. Solving an urban river erosion problem on the Tilmore Brook, Hampshire (UK). Water and Environment Journal, 19(3): 199-206.

Brown, K. B. 2000. Urban stream restoration practices: an initial assessment. The Center for Watershed Protection. Elliot City, MD.

Cairns, J., 1990. Lack of theoretical basis for predicting rate and pathways of recovery. Environmental Management, 14(5): 517-526.

Cals, M.J.R., Postma, R., Buijse, A.D. and Marteijn, E.C.L., 1998. Habitat restoration along the River Rhine in The Netherlands: putting ideas into practice. Aquatic Conservation-Marine and Freshwater Ecosystems, 8: 61-70.

Carpenter, D.D., Sinha, S.K., Brennan, K. and Slate, L.O., 2003. Urban stream restoration. Journal of Hydraulic Engineering-ASCE, 129(7): 491-493.

Charbonneau, R. and Resh, V.H., 1992. Strawberry Creek on the University-of-California, Berkeley Campus - a case-history of urban stream restoration. Aquatic Conservation-Marine and Freshwater Ecosystems, 2(4): 293-307.

Chin, A. 2006. Urban transformation of river landscapes in a global context. Geomorphology, 79: 460-487.

Chin, A. and Gregory, K.J., 2001. Urbanization and adjustment of ephemeral stream channels. Annals of the Association of American Geographers, 91(4): 595-608.

Chin, A. and Gregory, K.J., 2005. Managing urban river channel adjustments. Geomorphology, 69: 28-45.

City of Austin. 1995a. Watershed Protection, Stream Restoration Program. http://www.ci.austin.tx.us/watershed/erosion.htm> (December 2005).

City of Austin. 1995b. Smart Growth Initiative. http://www.ci.austin.tx.us/smartgrowth/> (December 2005).

City of Austin. 1995c. History of Flooding in Austin. http://www.ci.austin.tx.us/watershed/floodhistory.htm> (December 2006).

City of Austin. 2001a. Watershed Information. http://www.ci.austin.tx.us/watershed/learn_ws.htm> (February 2006).

City of Austin. 2001b. Stabilization projects. http://www.ci.austin.tx.us/watershed/erosion_projoverview.htm> (February 2006).

City of Austin. 2007. GIS Data Sets. ftp://ftp.ci.austin.tx.us/GIS-Data/Regional/coa_gis.html> (July 2007).

Davis, N.M., Weaver, V., Parks, K. and Lydy, M.J., 2003. An assessment of water quality, physical habitat, and biological integrity of an urban stream in Wichita, Kansas, prior to restoration improvements (phase I). Archives of Environmental Contamination and Toxicology, 44(3): 351-359.

Downs, P.W. and Kondolf, G.M., 2002. Post-project appraisals in adaptive management of river channel restoration. Environmental Management, 29(4): 477-496.

Doyle, M.W., Harbor, J.M., Rich, C.F. and Spacie, A., 2000. Examining the effects of urbanization on streams using indicators of geomorphic stability. Physical Geography, 21(2): 155-181.

Duncan, M.J., Suren, A.M., and Brown, S.L.R., 1999. Assessment of streambed stability in steep, bouldery streams: development of a new analytical technique. Journal of the North American Benthological Society, 18(4): 445-456.

Dunne, T. and Leopold, L.B., 1978. Water in Environmental Planning. W. H. Freeman and Company, San Francisco, CA.

Ellis, J.B., 1995. Integrated approaches for achieving sustainable development of urban storm drainage. Water Science and Technology, 32(1): 1-6.

Fisher, J.D. 2001. Elisabet Ney Museum. Handbook of Texas Online. <http://www.tsha.utexas.edu/handbook/online/articles/EE/kle1.html> (August 2007).

Gordon, N. D., T. A. McMahon, and B. L. Finlayson, 1992. Stream Hydrology: an Introduction for Ecologists. 2nd edition. Chichester, London.

Graf, W.L., 1985. Geomorphic measurements from ground-based photographs. *In*: A. Pitty (Ed), Geomorphology: Themes and Trends. Barnes and Noble Books, Totowa, NJ, pp. 211-225.

Gregory, K.J., 2002. Urban channel adjustments in a management context: an Australian example. Environmental Management, 29(5): 620-633.

Gregory, K.J. and Chin, A., 2002. Urban stream channel hazards. Area, 34(3): 312-321.

Grimm, N.B., Sheibley, R.W., Crenshaw, C.L., Dahm, C.N., Roach, W.J., et al., 2005. N retention and transformation in urban streams. Journal of the North American Benthological Society, 24(3): 626-642.

Groffman, P.M. and Dorsey, A.M., 2005. N processing within geomorphic structures in urban streams. Journal of North American Benthological Society, 24(3): 613-625.

Guilfoyle, M.P. and Fischer, R.A., 2006. Guidelines for establishing monitoring programs to assess the success of riparian restoration efforts in arid and semi-arid landscapes, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hammer, T.R., 1972. Stream channel enlargement due to urbanization. Water Resources Research, 8(6): 1530-1540.

Hancock, P.J., 2002. Human impacts on the stream-groundwater exchange zone. Environmental Management, 29(6): 763-781.

Harremoes, P., Napstjert, L., Rye, C., Larsen, H.O. and Dahl, A., 1996. Impact of rain runoff on oxygen in an urban river. Water Science and Technology, 34(12): 41-48.

Harris, D.L., 2002. Effects of urbanization on stream channel morphology, Madisonville, Texas, Texas A&M University, College Station, TX.

Helfield, J.M. and Diamond, M.L., 1997. Use of constructed wetlands for urban stream restoration: A critical analysis. Environmental Management, 21(3): 329-341.

Johnson, P.A., Tereska, R.L. and Brown, E.R., 2002. Using technical adaptive management to improve design guidelines for urban instream structures. Journal of the American Water Resources Association, 38(4): 1143-1152.

Kasahara, T. and Hill, A.R., 2006. Effects of riffle-step restoration on hyporheic zone chemistry in N-rich lowland streams. Canadian Journal of Fisheries and Aquatic Sciences, 63(1): 120-133.

Kirpich, P.Z., 1940. Time of concentration of small agricultural watersheds. Civil Engineering, 10: 362.

Kondolf, G.M., 1995. Five elements for effective evaluation of stream restoration. Restoration Ecology, 3(2): 133-136.

Kondolf, G.M., 1996. A cross section of stream channel restoration. Journal of Soil and Water Conservation: 119-125.

Kondolf, G.M., 1998. Lessons learned from river restoration projects in California. Aquatic Conservation-Marine and Freshwater Ecosystems, 8(1): 39-52.

Kondolf, G.M. and Micheli, E.R., 1995. Evaluating stream restoration projects. Environmental Management, 19(1): 1-15.

Kondolf, G.M., Piegay, H. and Sear, D., 2002. Integrating geomorphological tools in ecological and management studies. In: Kondolf, G.M. and Piegay, H. (Eds), Tools in Fluvial Geomorphology. John Wiley and Sons, Inc., Hoboken, NJ, pp. 633-660.

Lake, P.S., 2005. Perturbation, restoration and seeking ecological sustainability in Australian flowing waters. Hydrobiologia, 552: 109-120.

Larson, M.G., Booth, D.B. and Morley, S.A., 2001. Effectiveness of large woody debris in stream rehabilitation projects in urban basins. Ecological Engineering, 18(2): 211-226.

Lassettre, N.S., 1997. Evaluation of structures to improve steelhead trout (*Oncorhynchus mykiss*) habitat, San Jose State University, San Jose, CA.

Li, M. and Eddleman, K.E., 2002. Biotechnical engineering as an alternative to traditional engineering methods: A biotechnical streambank stabilization design approach. Landscape and Urban Planning, 60: 225-242.

Li, M., Landpahir, H.C., Arnold, M.A., Mullin, K. and Eddleman, K.E., 2005. A dormancy extension technique for biotechnical streambank stabilization in warm regions. Landscape and Urban Planning, 71: 223-231.

Marsh, W.M. and Marsh, N.L., 1995. Hydrogeomorphic considerations in development planning and stormwater management, central Texas hill country, USA. Environmental Management, 19(5): 693-702.

Maughan, E.O. and Nelson, K.L., 1980. Improving stream fisheries. Water Spectrum, 12: 10-15.

Meyer, J.L., Paul, M.J. and Taulbee, W.K., 2005. Stream ecosystem function in urbanizing landscapes. Journal of North American Benthological Society, 24(3): 602-612.

Middleton, J.V., 2001. The stream doctor project: community-driven stream restoration. BioScience, 4: 293-296.

National Research Council, 1992. Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy. National Academy Press, Washington, DC.

Niezgoda, S.L. and Johnson, P.A., 2005. Improving the urban stream restoration effort: identifying critical form and processes relationships. Environmental Management, 35(5): 579-592.

Nolan, P.A. and Guthrie, N., 1998. River rehabilitation in an urban environment: examples from the Mersey Basin, North West England. Aquatic Conservation-Marine and Freshwater Ecosystems, 8(5): 685-700.

Palmer, M.A. and Bernhardt, E.S., 2006. Hydroecology and river restoration: Ripe for research and synthesis. Water Resources Research, 42(3).

Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., et al., 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology, 42: 208-217.

Paul, M.J. and Meyer, J.L., 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics, 32: 333-365.

Pfankuch, D. J. 1975. Stream reach inventory and channel stability evaluation. United States Department of Agriculture Forest Service. Government Printing Office #696-260/200, Washington, DC, Rl-75-002.

Pizzuto, J.E., Hession, W.C. and McBride, M., 2000. Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. Geology, 28(1): 79-82.

Price, D.J. and Birge, W.J., 2005. Effectiveness of stream restoration following highway reconstruction projects on two freshwater streams in Kentucky. Ecological Engineering, 25: 73-84.

Proctor, C.V., Brown, T.E., McGowen, J.H. and Waechter, N.B., 1974. Geologic Atlas of Texas, Austin Sheet. University of Texas, Bureau of Economic Geology, Austin.

Purcell, A.H., Friedrich, C. and Resh, V.H., 2002. An assessment of a small urban stream restoration project in northern California. Restoration Ecology, 10(4): 685-694.

Rasmussen, G. A. and K. Voth. 2001. Repeat photography monitoring made easy. Utah State University Extension Publication NR-504. Logan, Utah.

Rhoads, B.L., Wilson, D., Urban, M. and Herricks, E.E., 1999. Interaction between scientists and nonscientists in community-based watershed management: emergence of the concept of stream naturalization. Environmental Management, 24(3): 297-308.

Rosgen, D.L., 1994. A classification of natural rivers. Catena, 22: 169-199.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, CO.

Rosgen, D.L., 2001. A stream channel stability assessment methodology. Proceedings of the Seventh Federal Interagency Sedimentation Conference, Vol. 2; 2001 Mar 25-29; Reno (NV): 18-26.

Rosgen, D.L., 2004. Restoration WARSSS. Annual Meeting of the American Society of Agricultural and Biological Engineers. St. Joseph, MI.

Ryder, D.S. and Miller, W., 2005. Setting goals and measuring success: linking patterns and processes in stream restoration. Hydrobiologia, 552: 147-158.

Schauman, S. and Salisbury, S., 1998. Restoring nature in the city: Puget Sound experiences. Landscape and Urban Planning, 42(2-4): 287-295.

Shields, F.D., Jr., Knight, S.S. and Cooper, C.M., 1998. Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Missippi. Hydrobiologia, 382: 63-86.

Smith, S., 1997. Changes in the hydraulic and morphological characteristics of a relocated stream channel, University of Maryland, Annapolis.

Suren, A.M. and McMurtrie, S., 2005. Assessing the effectiveness of enhancement activities in urban streams: II. Responses of invertebrate communities. River Research and Applications, 21(4): 439-453.

Suren, A.M., Riis, T., Biggs, B.J.F., McMurtrie, S. and Barker, R., 2005. Assessing the effectiveness of enhancement activities in urban streams: I. Habitat responses. River Research and Applications, 21(4): 381-401.

Texas Parks and Wildlife Department (TPWD). 2005a. Blackland Prairie Ecological Region. http://www.tpwd.state.tx.us/landwater/land/habitats/cross_timbers/ecoregions/blackland.phtml> (December 2006).

Texas Parks and Wildlife Department (TPWD). 2005b. Edwards Plateau Ecological Region. http://www.tpwd.state.tx.us/landwater/land/habitats/cross_timbers/ecoregions/edwards_plateau.phtml> (December 2006).

Texas Water Development Board (TWDB). 2006. 2007 State Water Plan. TWDB GP-8-1.

Townsend, C.R., Scarsbrook, M.R., and Doledec, S., 1997. Quantifying disturbance in streams: alternative measures of disturbance in relation to macroinvertebrate species traits and species richness. Journal of the North American Benthological Society, 16(3): 531-544.

Tunstall, S.M., Penning-Rowsell, E.C., Tapsell, S.M. and Eden, S.E., 2000. River restoration: public attitudes and expectations. Journal of the Chartered Institution of Water and Environmental Management, 14(5): 363-370.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., et al., 2005a. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society, 24(3): 706-723.

Walsh, C.J., Fletcher, T.D. and Ladson, A.R., 2005b. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. Journal of the North American Benthological Society, 24(3): 690-705.

Walter, R.C. and Merritts, D.J. 2008. Natural streams and the legacy of water-powered mills. Science, 319(5861): 299-304.

Wohl, E. et al., 2005. River restoration. Water Resources Research, 41, W10301, doi:10.1029/2005WR003985.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Transactions of the American Geophysical Union, 35: 951-956.

Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler, 49A: 385-395.

APPENDIX A

Table A-1. Field sheet for stream reach stability evaluation (Pfankuch, 1975).

UPPER BANKS	**EXCELLENT**		**GOOD**		**FAIR**		**POOR**	
Landform slope	Bank slope gradient <30%	2	Bank slope gradient 30-40%	4	Bank slope gradiet 40-60%	6	Bank slope gradient >60%	8
Mass-wasting (existing or potential)	No evidence of past or any potential for future mass wasting into channel	3	Infrequent and/or very small. Mostly healed over. Low future potential	6	Moderate frequency and size, with some raw spots eroded by water during high flows	9	Frequent of large, causing sediment or imminent danger of same.	12
Debris jam potential (floatable objects)	Essentially absent from immediate channel area	2	Present but mostly small twigs and limbs	4	Present, volumen and size are both increasing	6	Moderate to heavy amounts, mainly larger sizes	8
Vegetative bank protection	>90% plant density. Vigor and variety suggests a deep, dense, soil binding root mass	3	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass	6	50-70% density. Lower vigor and species form a somewhat shallow and discontinuous root mass	9	<50% density plus fewer species and viogor indicate discontinuous and shallow root mass	12
Channel capacity	Ample for present plus some increases. Peak flows contained. Width to depth (W/D) ratio <7	1	Adequate. Overbank flows rare. W/D ratio 8 to 15	2	Barely contains present peaks. Occasional overbank floods. W/D ratio 15 to 25	3	Inadequate. Overbank flows common. W/D ratio >25	4
LOWER BANKS								
Bank rock content	65% with large, angular boulders 30 cm numerous	2	40 to 65%, mostly small boulders to cobbles 15-30cm	4	20 to 40%, with most in the .5-15cm diameter class	6	<20% rock fragments of gravel sizes, 2.5-7.5cm or less	8
Obstructions (flow deflectors; sediment traps)	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	2	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm	4	Moderately frequent, unstable obstructions and deflectors move with high water causing bank cutting and filling of pools	6	Frequent obstructions and deflectors cause bank erosion. Sediment traps, full channel migration occurring	8
Undercutting	Little or none evident. Infrequent raw banks <150cm high	4	Some, intermittently at outcurves and constrictions. Raw banks <30cm	8	Significant. Cuts 15-30cm high. Root mat overhangs and sloughing evident	12	Almost continuous cuts, some >30cm high. Failure of overhangs frequent	16
Deposition	Little or no enlargement of channel or point bars.	4	Some new increase in bar formation, mostly from coarse gravels.	8	Moderate deposition of new gravel and coarse sand on old and some new bars.	12	Extensive deposits of predominantly fine particles. Accelerated bar development	16
STREAM BED								
Rock angularity	Sharp edges and corners, plane surfaces roughened.	1	Rounded corners and edges. Smooth and flat.	2	Corners and edges well rounded in two dimensions	3	Well rounded in all dimensions.	4
Brightness	Surfaces dull, darkened or stained. Not "bright".	1	Mostly dull, but may have up to 35% bright surfaces.	2	Mixture, 50-50% dull and bright i.e. 35-65%.	3	Predominantly bright, 65%, exposed surfaces.	4
Consolidation or particle packing	Assorted sizes tightly packed and/or overlapping.	2	Moderately packed with some overlapping.	4	Mostly a loose assortment with no apparent overlap.	6	No packing evident. Loose, easily moved.	8
Bottom size distribution & stable	No change in sizes evident. Stable materials 80-100%	4	Distribution shift slight. Stable materials 50-80%.	8	Moderate change in sizes. Stable materials 20-50%	12	Marked change. Stable materials 0-20%	16
Scouring and deposition	<5% of the bottom affected by scouring and deposition.	6	5-30% affected. Scour at constrictions and where steep. Pool deposition.	12	30-50% affected. Deposits and scour at obstructions, constrictions, and bends.	18	> 50% of bed in a state of flux or change nearly year-long.	24
Clinging aquatic vegetation (moss and algae)	Abundant, growth largely moss, dark green, perennial. In swift water too.	1	Common. Algal forms in low velocity and pool areas. Moss and swifter waters.	2	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick	3	Perennial types scarce or absent. Yellow-green, short term bloom present.	4
COLUMN TOTALS		0		0		0		0

Reach score of: <38 = Excellent, 39-76 = Good, 77-114 = Fair, 115+ = Poor

APPENDIX B

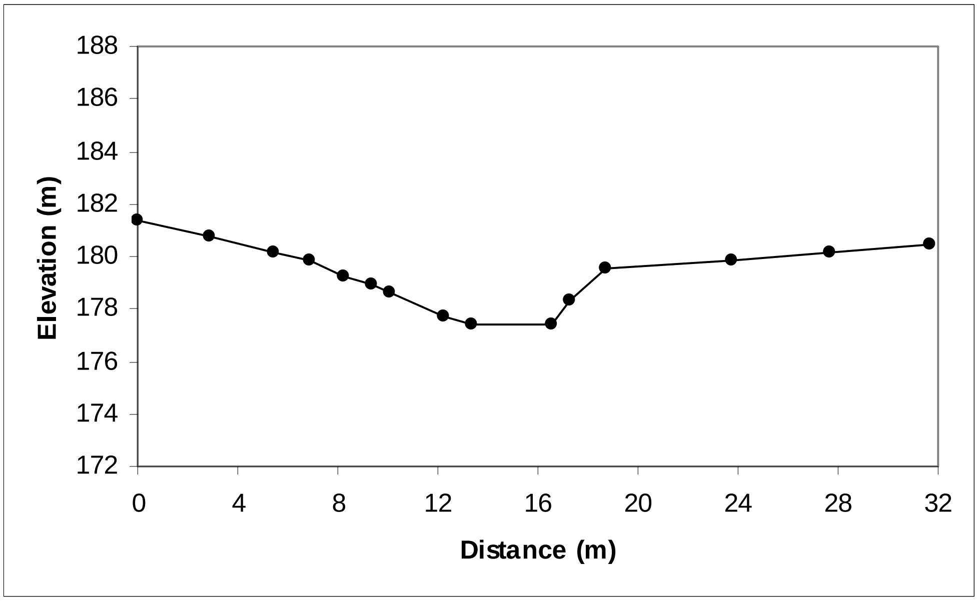

Figure B-1. Cross-section of Tannehill Branch at Bartholomew Park Pool 1 from City of Austin topographic survey before restoration, 2003.

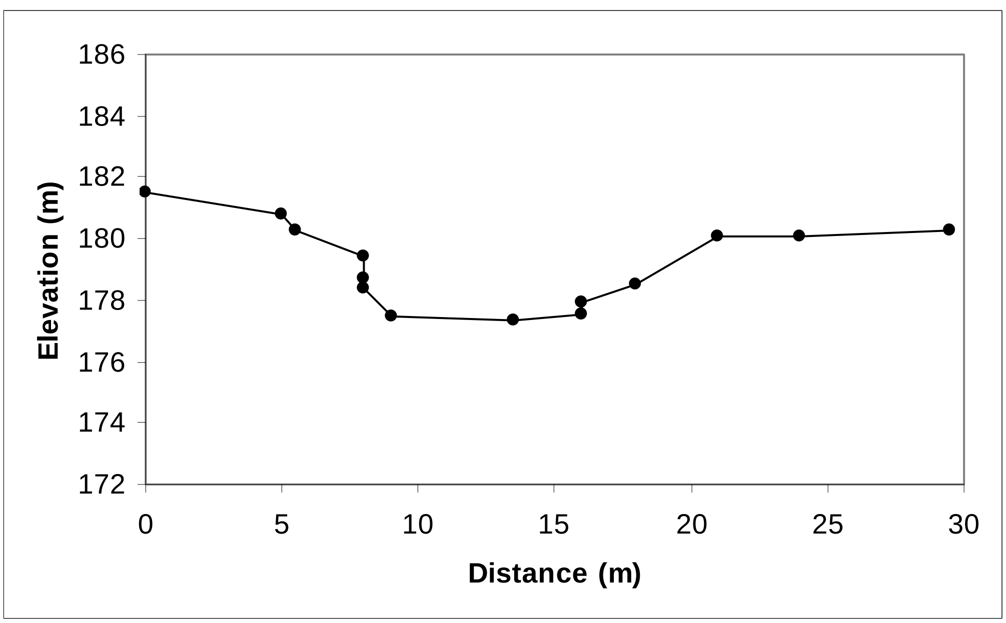

Figure B-2. Cross-section of Tannehill Branch at Bartholomew Park Pool 1 after restoration, 2007.

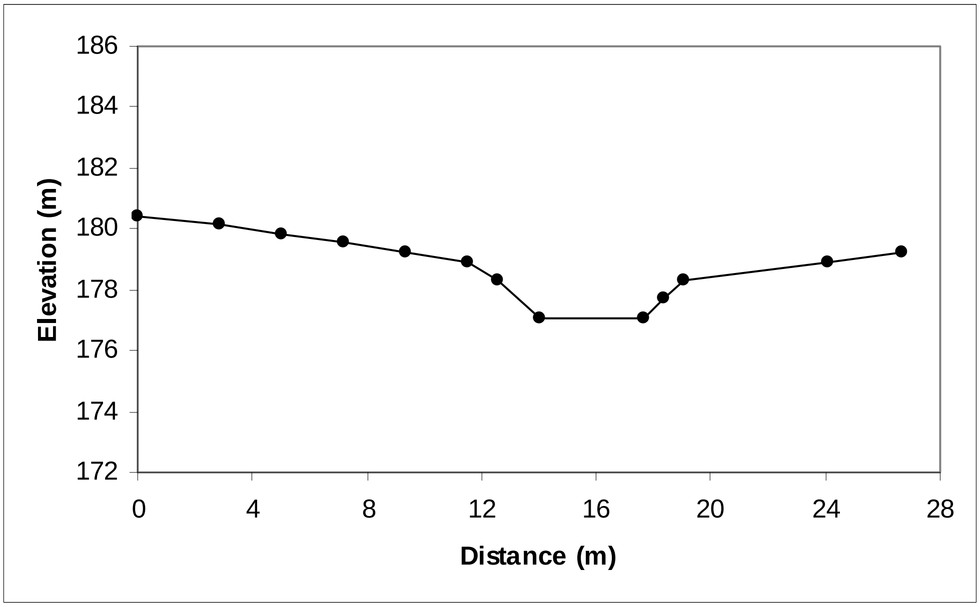

Figure B-3. Cross-section of Tannehill Branch at Bartholomew Park Riffle 1 from City of Austin topographic survey before restoration, 2003.

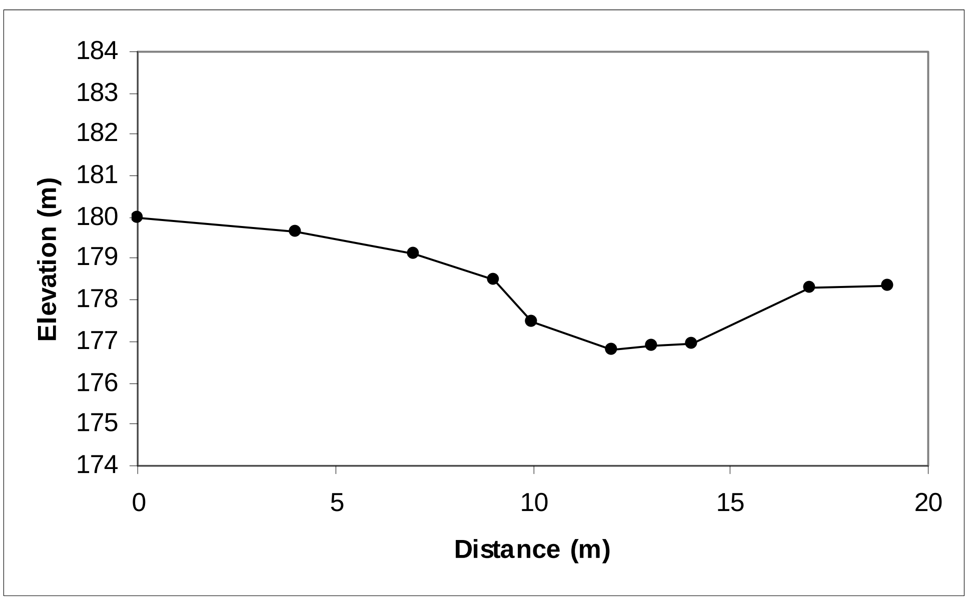

Figure B-4. Cross-section of Tannehill Branch at Bartholomew Park Riffle 1 after restoration, 2007.

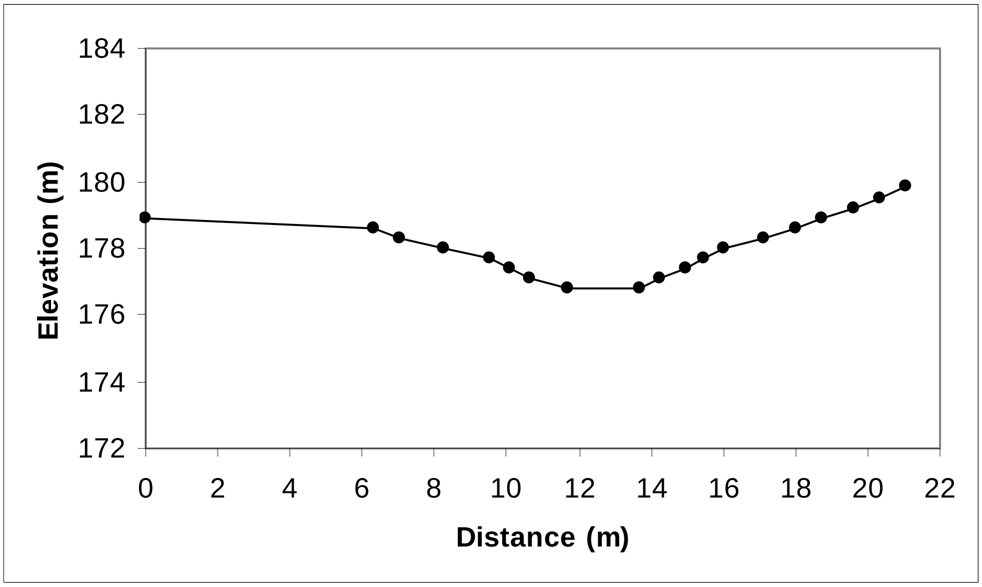

Figure B-5. Cross-section of Tannehill Branch at Bartholomew Park Pool 2 from City of Austin topographic survey before restoration, 2003.

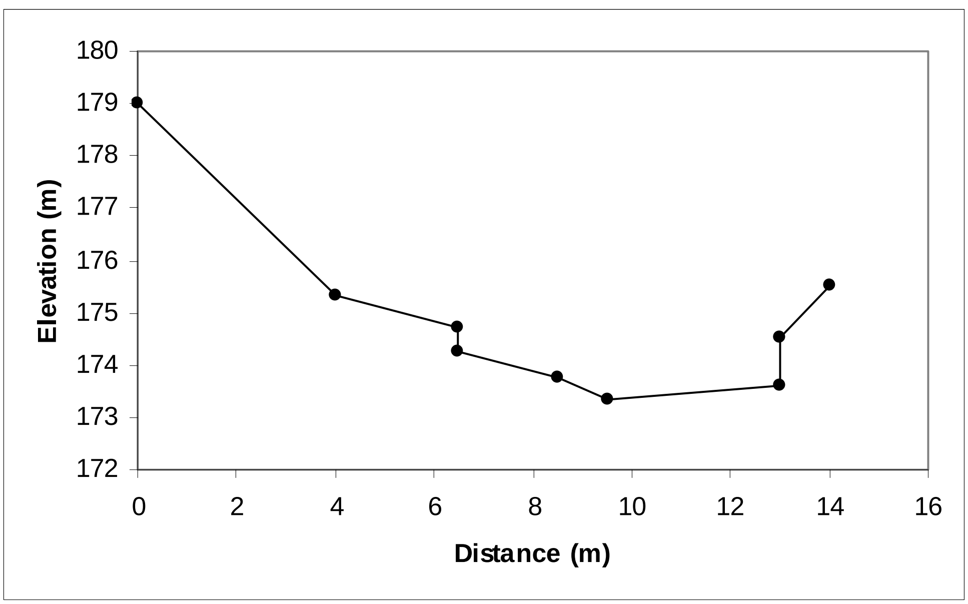

Figure B-6. Cross-section of Tannehill Branch at Bartholomew Park Pool 2 after restoration, 2007.

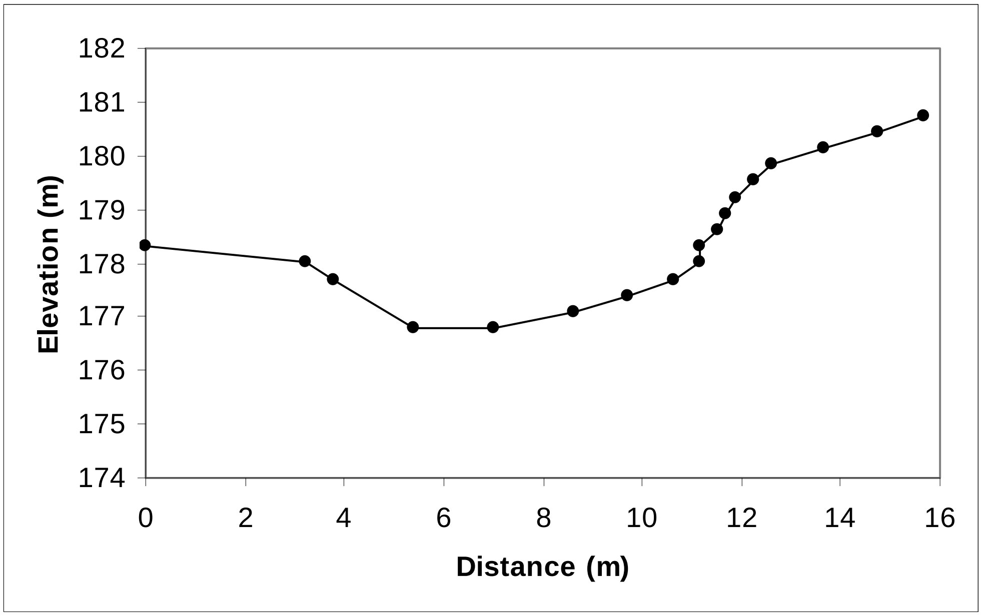

Figure B-7. Cross-section of Tannehill Branch at Bartholomew Park Riffle 2 from City of Austin topographic survey before restoration, 2003.

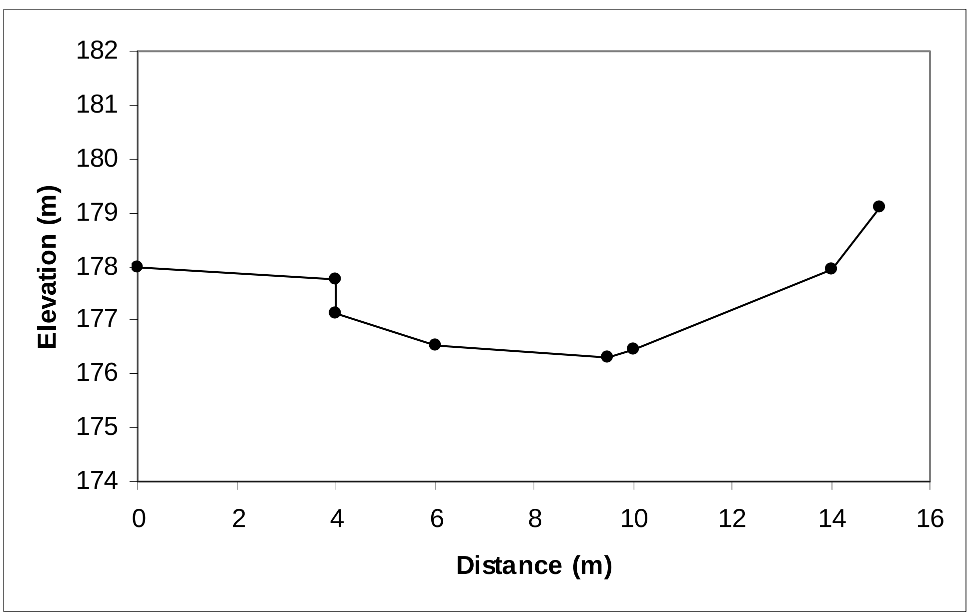

Figure B-8. Cross-section of Tannehill Branch at Bartholomew Park Riffle 2 after restoration, 2007.

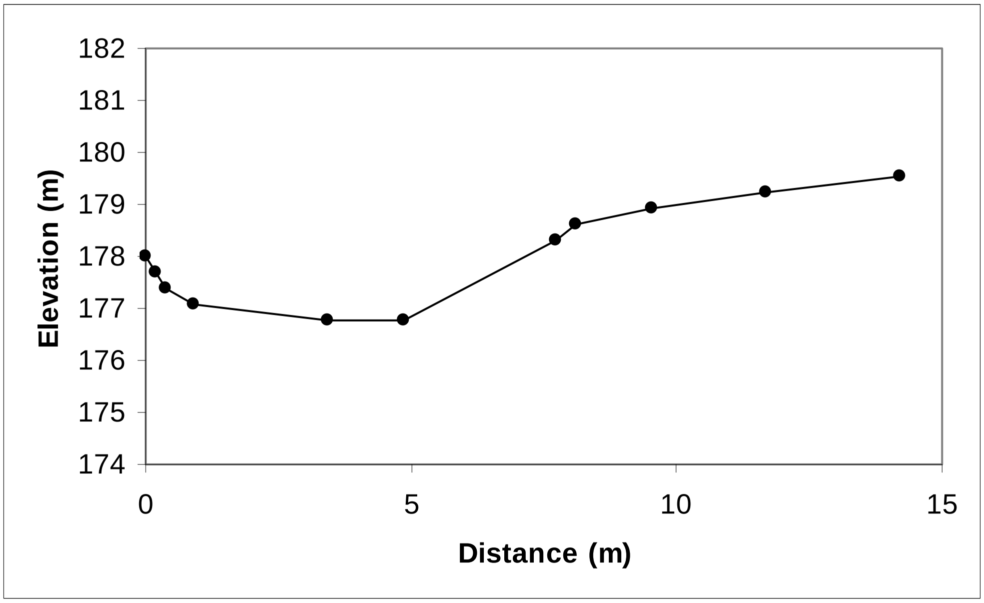

Figure B-9. Cross-section of Tannehill Branch at Bartholomew Park Pool 3 from City of Austin topographic survey before restoration, 2003.

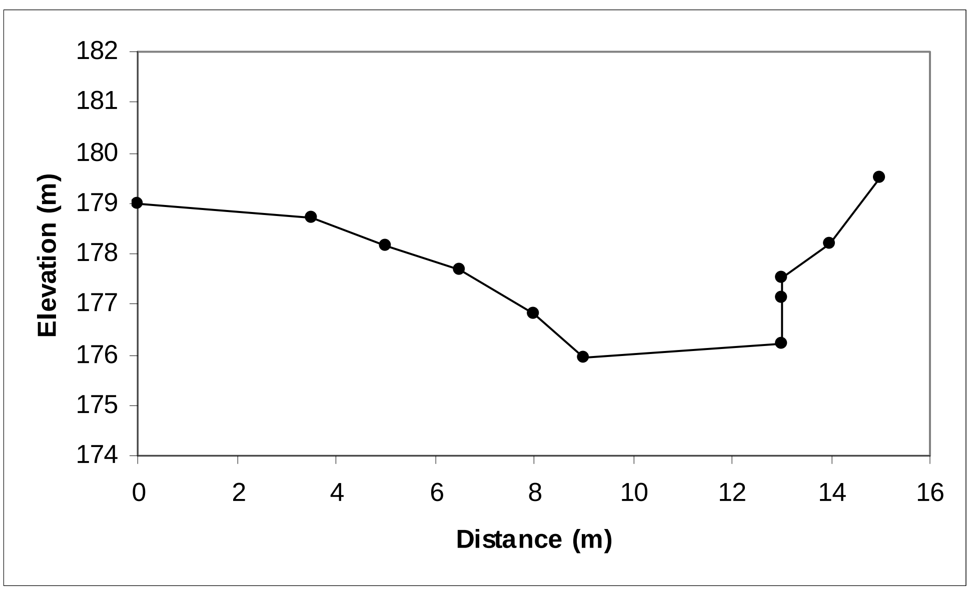

Figure B-10. Cross-section of Tannehill Branch at Bartholomew Park Pool 3 after restoration, 2007.

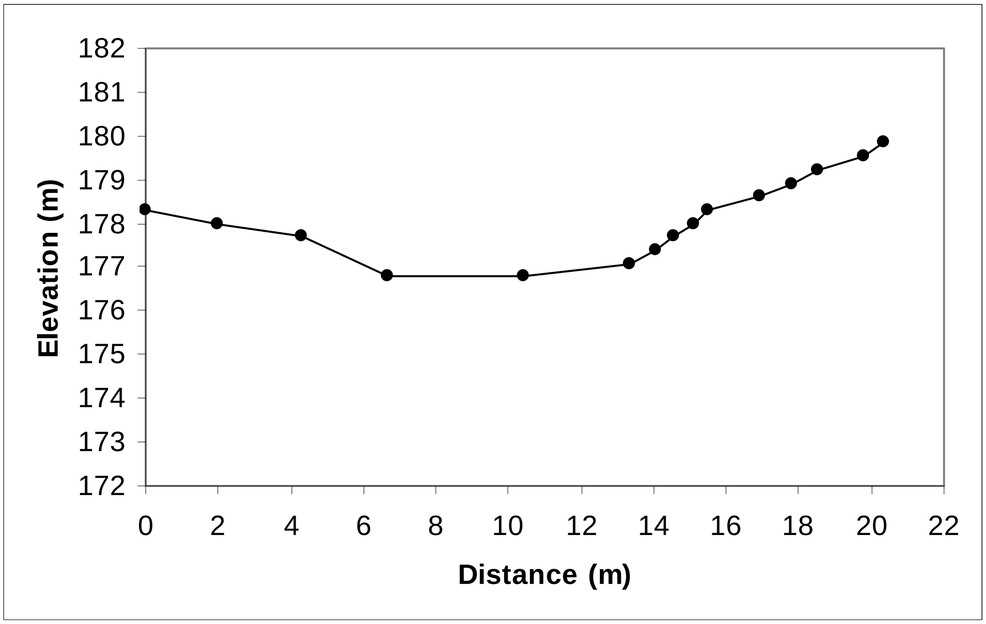

Figure B-11. Cross-section of Tannehill Branch at Bartholomew Park Riffle 3 from City of Austin topographic survey before restoration, 2003.

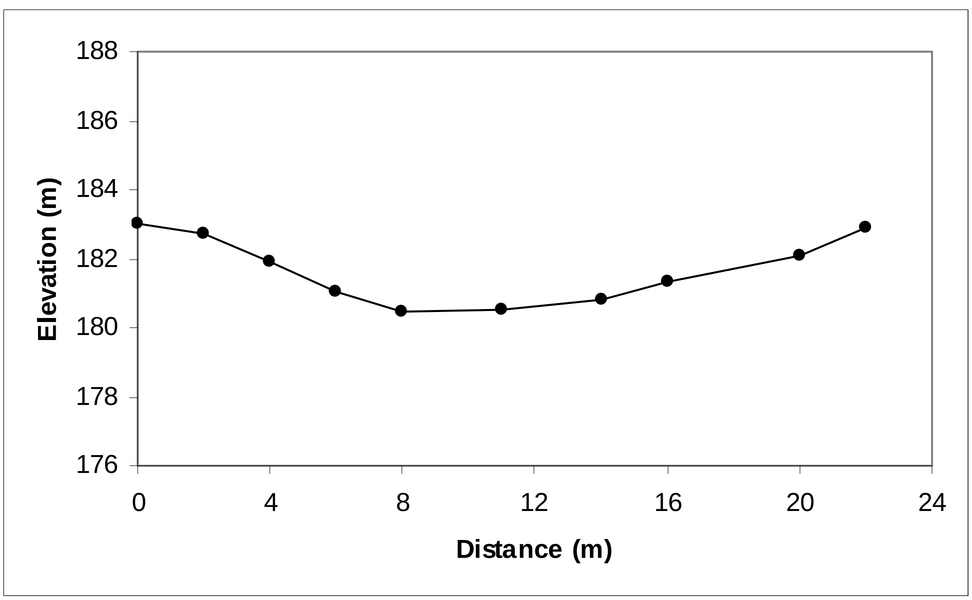

Figure B-12. Cross-section of Tannehill Branch at Bartholomew Park Riffle 3 after restoration, 2007.

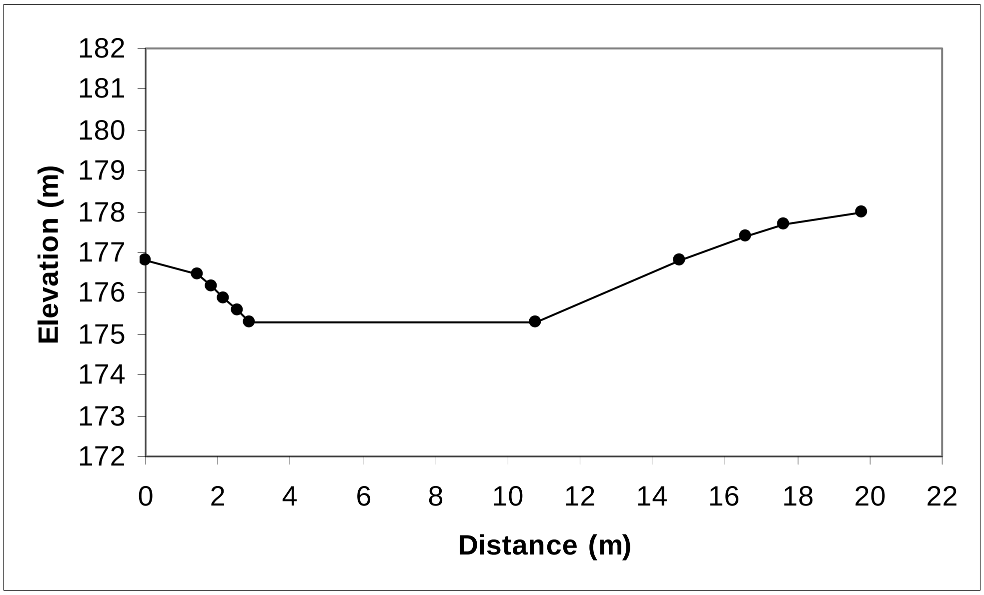

Figure B-13. Cross-section of Tannehill Branch at Bartholomew Park Pool 4 from City of Austin topographic survey before restoration, 2003.

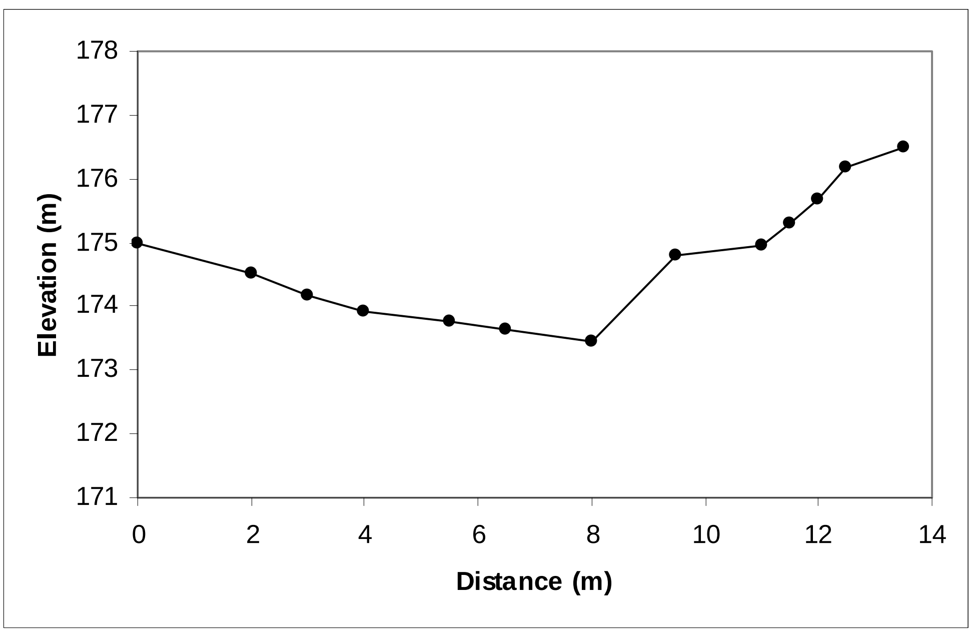

Figure B-14. Cross-section of Tannehill Branch at Bartholomew Park Pool 4 after restoration, 2007.

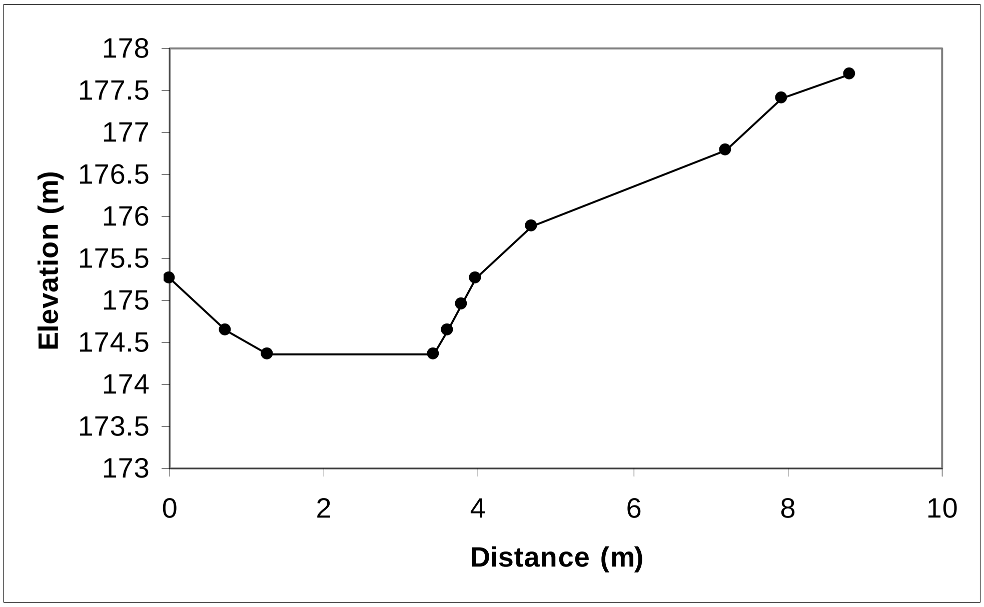

Figure B-15. Cross-section of Tannehill Branch at Bartholomew Park Riffle 4 from City of Austin topographic survey before restoration, 2003.

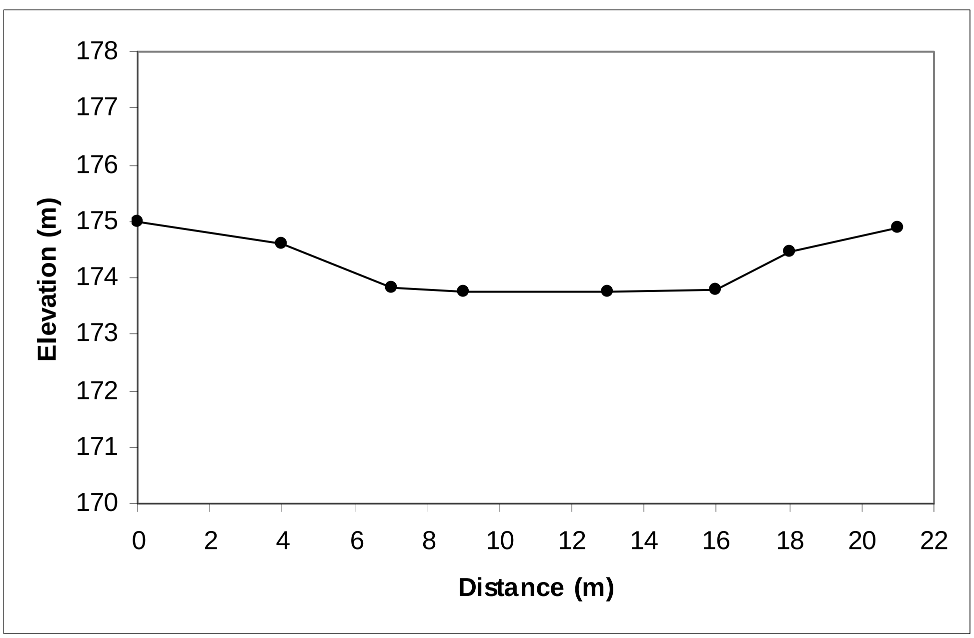

Figure B-16. Cross-section of Tannehill Branch at Bartholomew Park Riffle 4 after restoration, 2007.

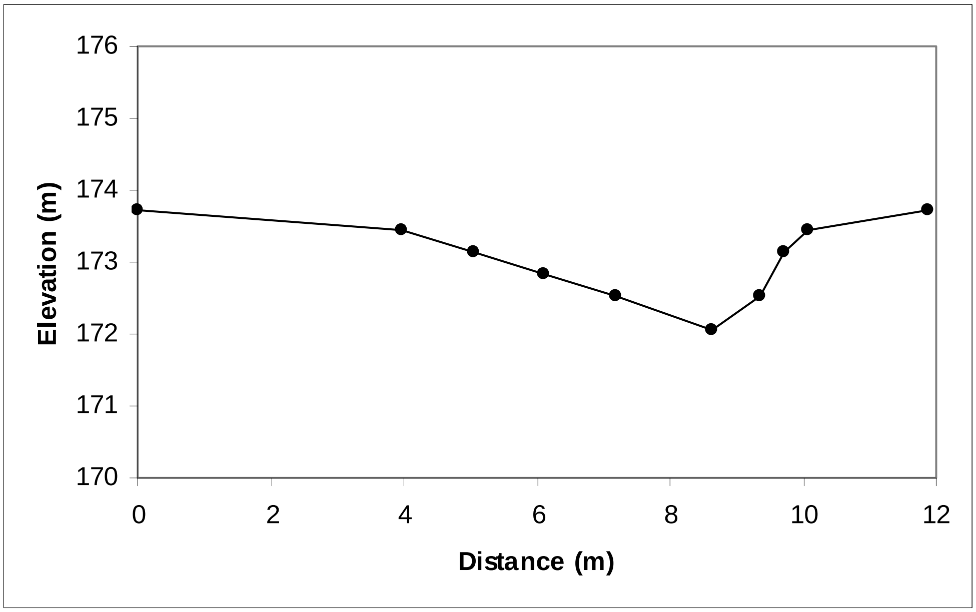

Figure B-17. Cross-section of Tannehill Branch at Bartholomew Park Pool 5 from City of Austin topographic survey before restoration, 2003.

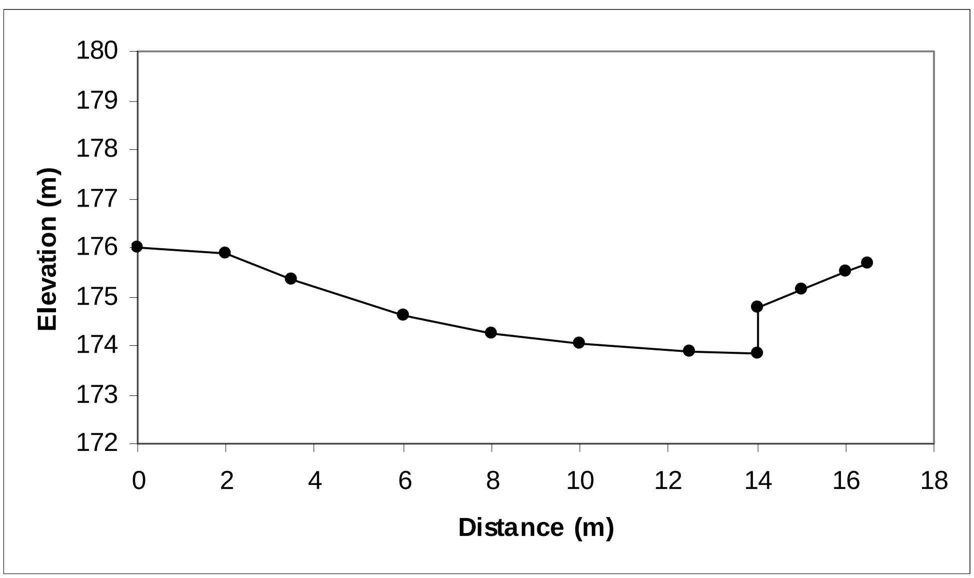

Figure B-18. Cross-section of Tannehill Branch at Bartholomew Park Pool 5 after restoration, 2007.

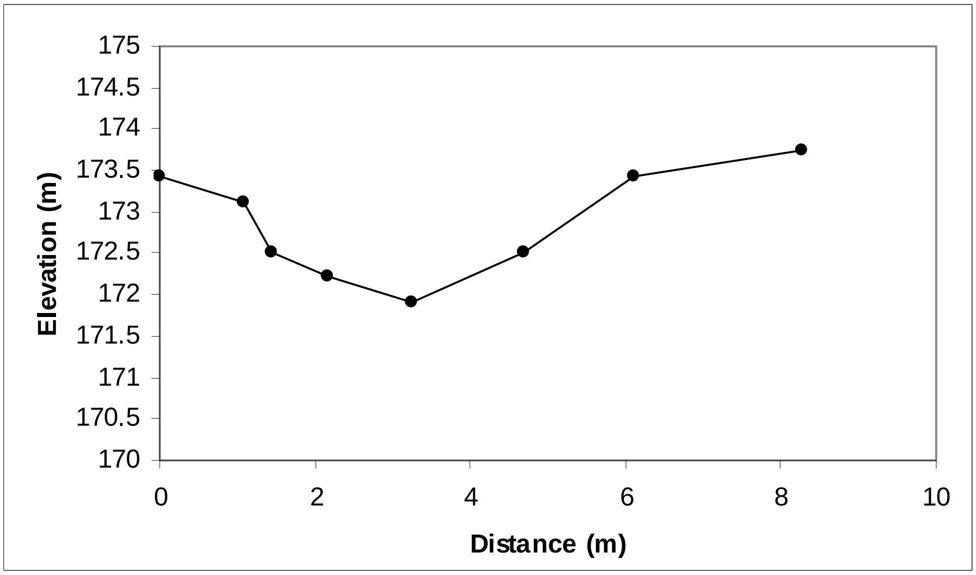

Figure B-19. Cross-section of Tannehill Branch at Bartholomew Park Riffle 5 from City of Austin topographic survey before restoration, 2003.

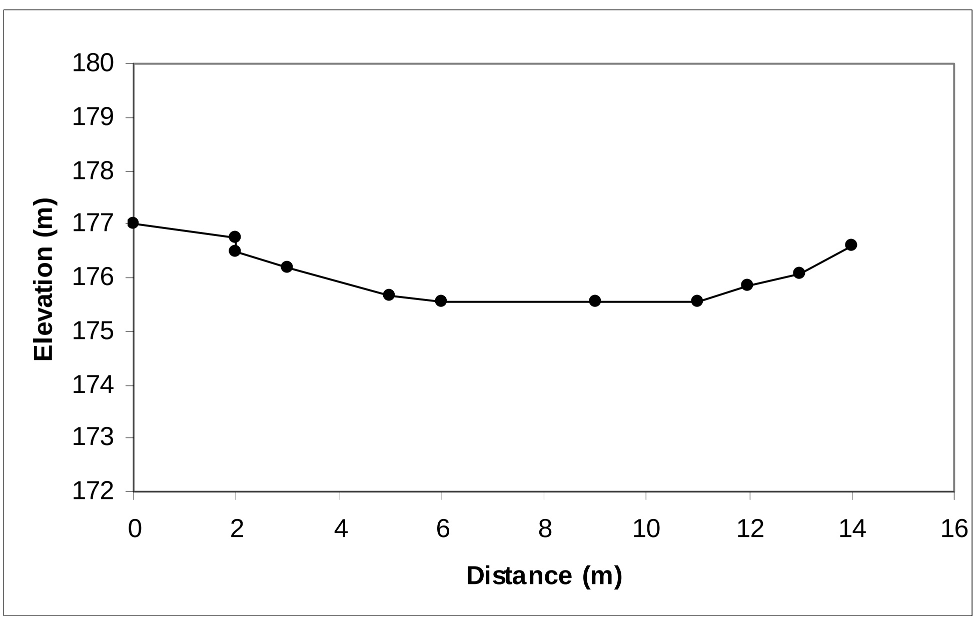

Figure B-20. Cross-section of Tannehill Branch at Bartholomew Park Riffle 5 after restoration, 2007.

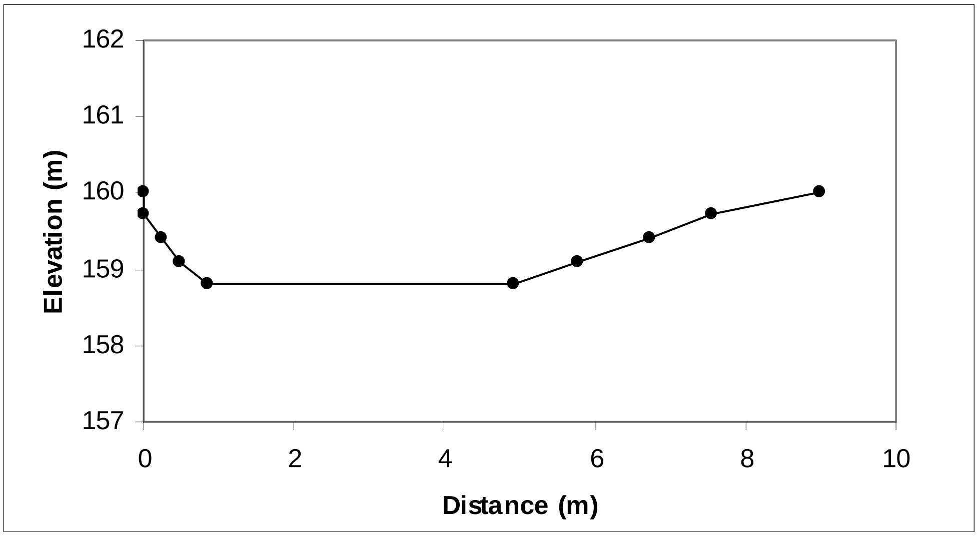

Figure B-21. Cross-section of Tannehill Branch at Lovell Drive Pool 1 from City of Austin topographic survey before restoration, 2003.

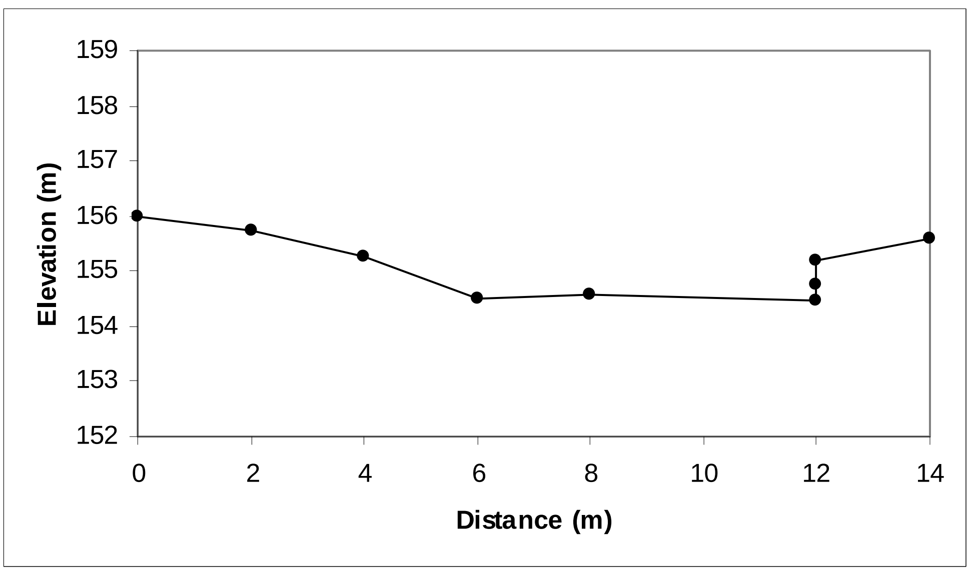

Figure B-22. Cross-section of Tannehill Branch at Lovell Drive Pool 1 after restoration, 2007.

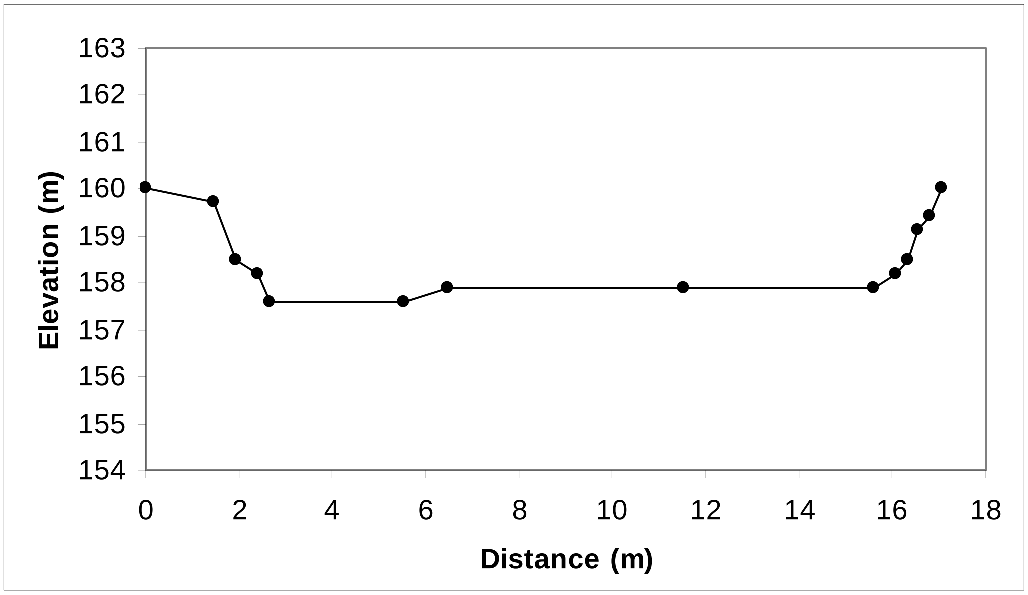

Figure B-23. Cross-section of Tannehill Branch at Lovell Drive Pool 2 from City of Austin topographic survey before restoration, 2003.

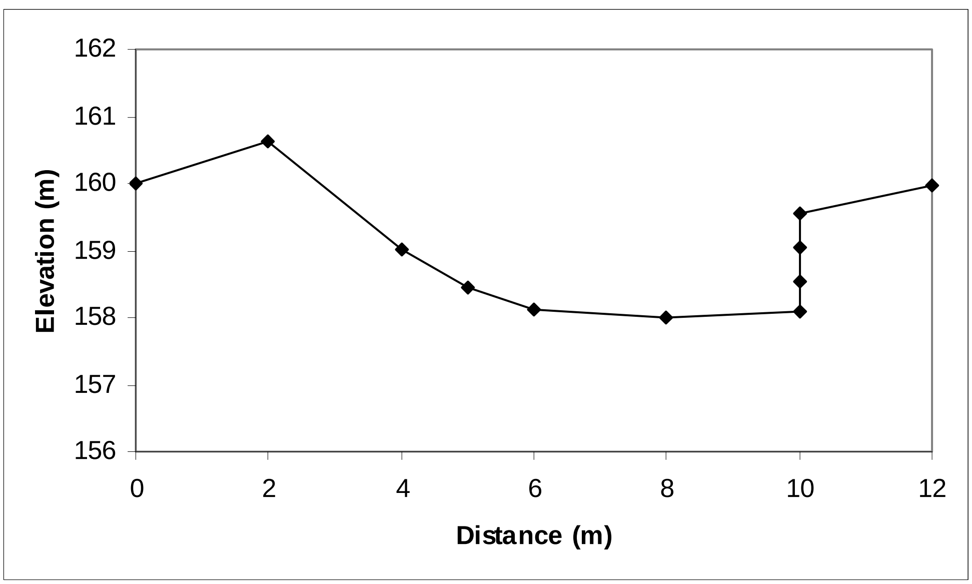

Figure B-24. Cross-section of Tannehill Branch at Lovell Drive Pool 2 after restoration, 2007.

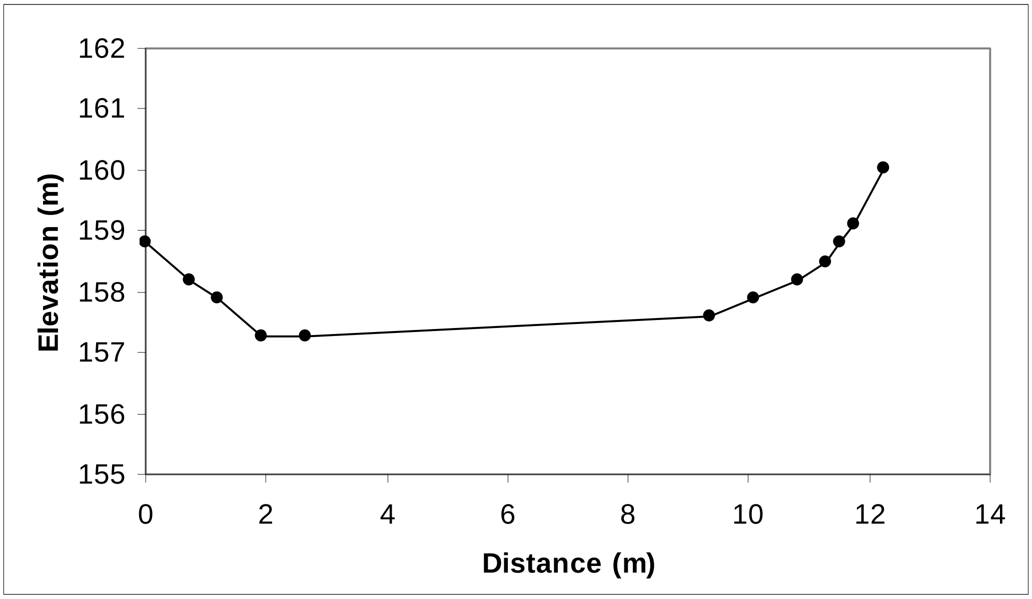

Figure B-25. Cross-section of Tannehill Branch at Lovell Drive Riffle 2 from City of Austin topographic survey before restoration, 2003.

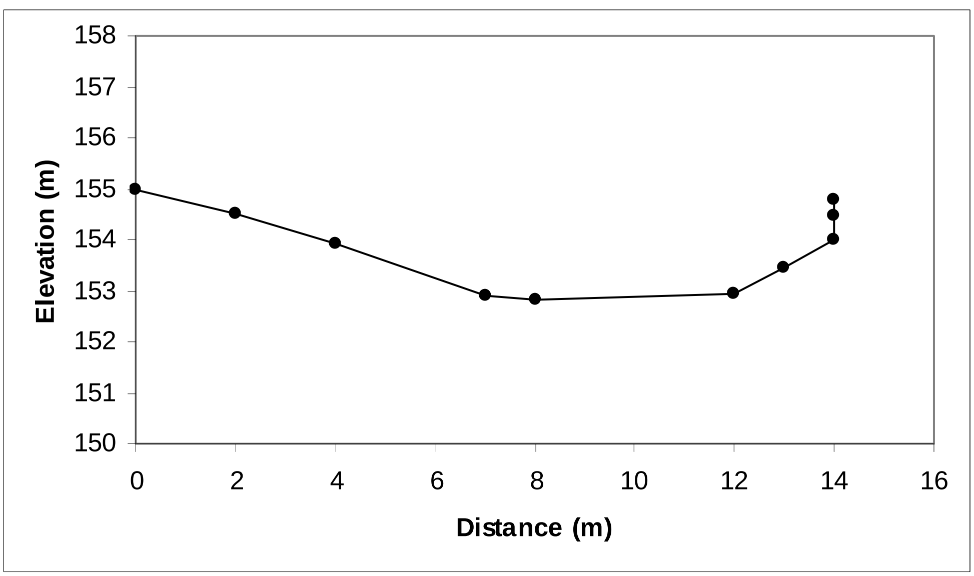

Figure B-26. Cross-section of Tannehill Branch at Lovell Drive Riffle 2 after restoration, 2007.

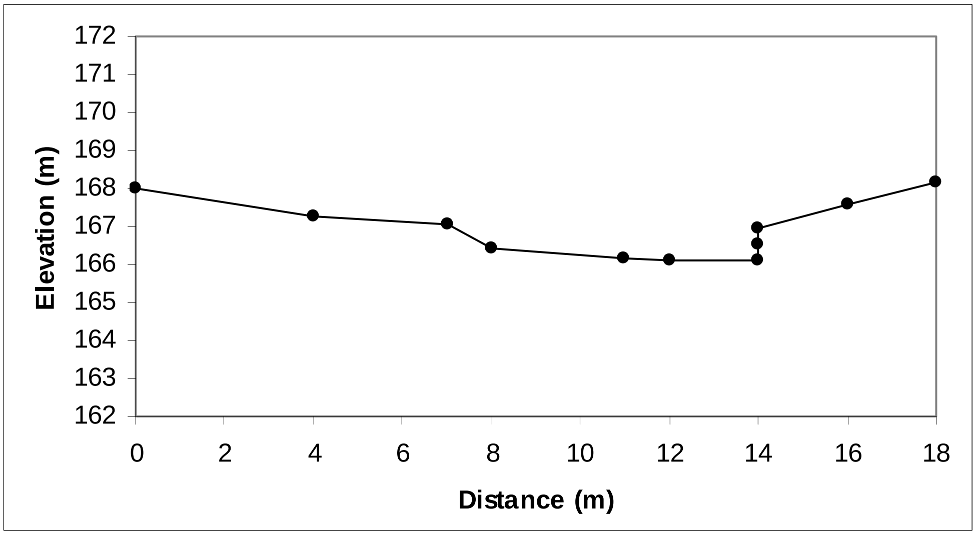

Figure B-27. Cross-section of Tannehill Branch at Lovell Drive Riffle 1 after restoration, 2007.

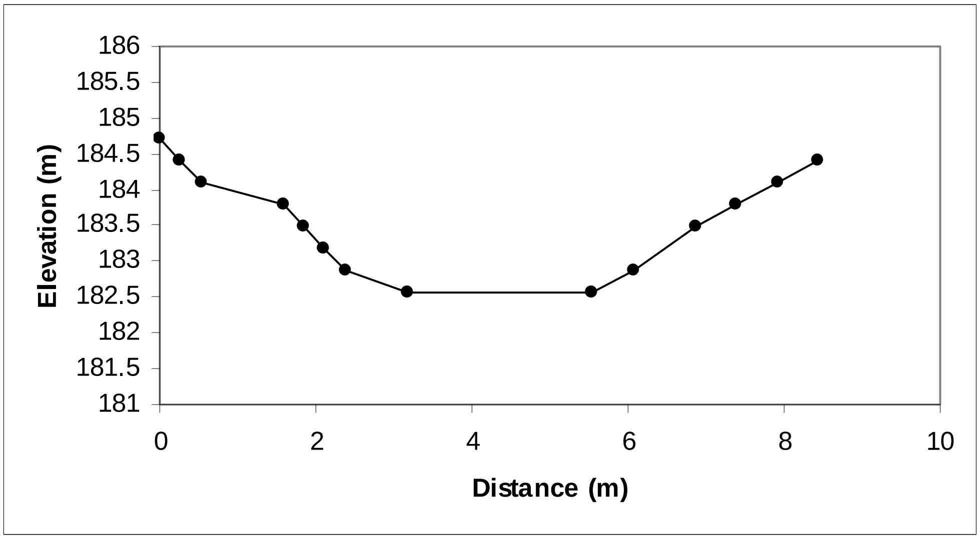

Figure B-28. Cross-section of Waller Creek at Shipe Park Pool 1 from City of Austin topographic survey before restoration, 1995.

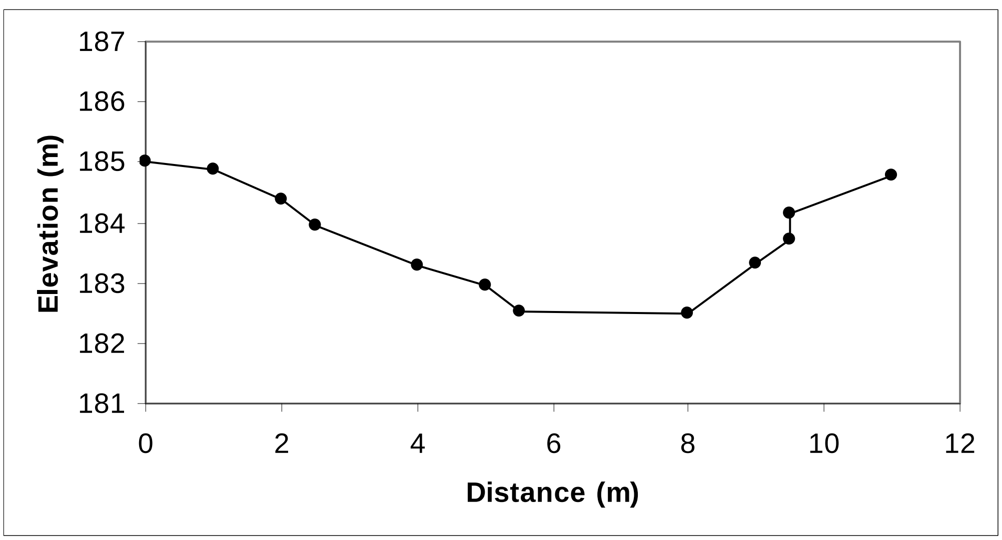

Figure B-29. Cross-section of Waller Creek at Shipe Park Pool 1 after restoration, 2007.

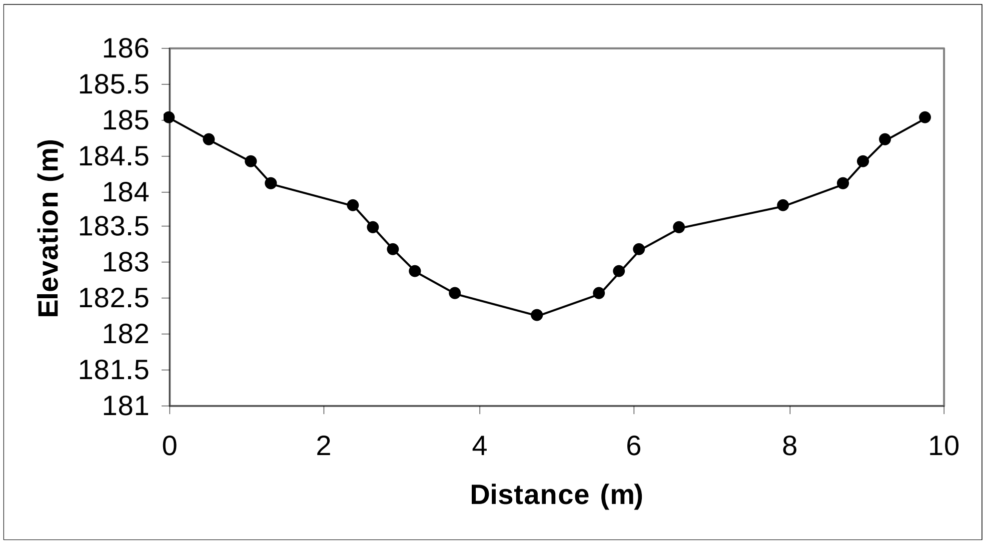

Figure B-30. Cross-section of Waller Creek at Shipe Park Riffle 1 from City of Austin topographic survey before restoration, 1995.

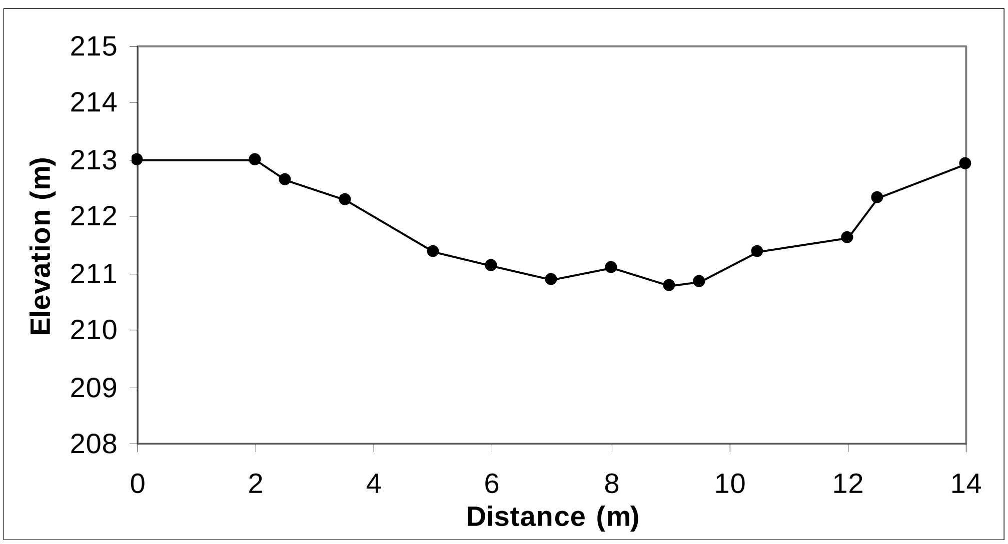

Figure B-31. Cross-section of Waller Creek at Shipe Park Riffle1 after restoration, 2007.

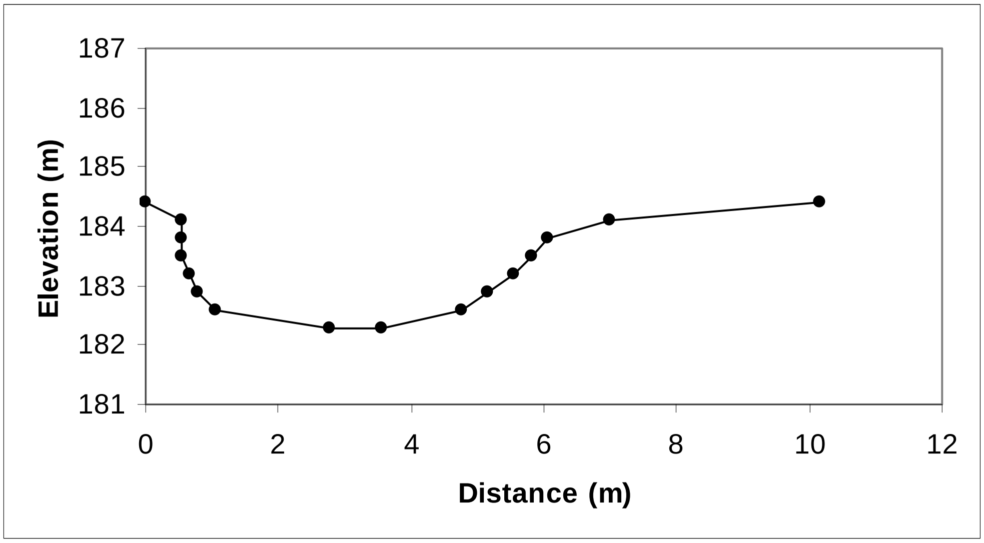

Figure B-32. Cross-section of Waller Creek at Shipe Park Pool 2 from City of Austin topographic survey before restoration, 1995.

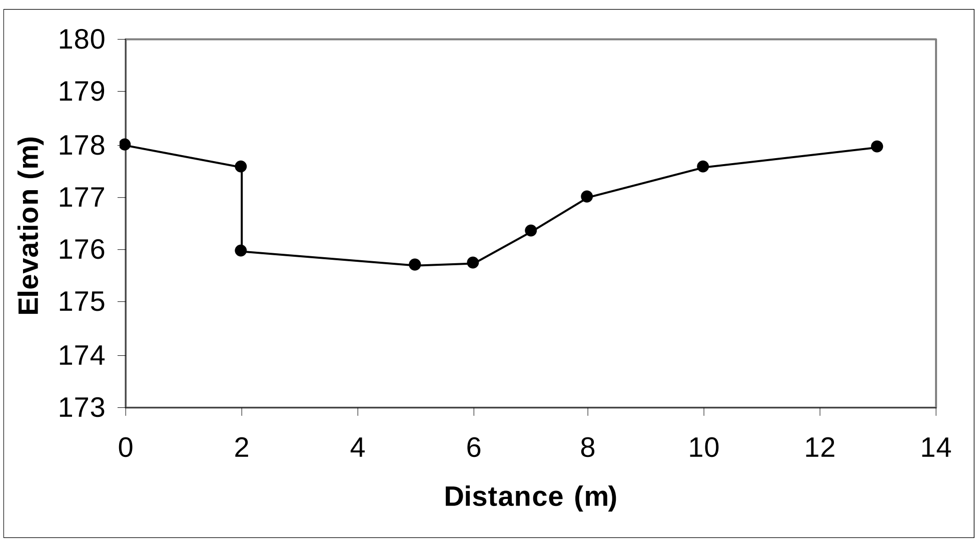

Figure B-33. Cross-section of Waller Creek at Shipe Park Pool 2 after restoration, 2007.

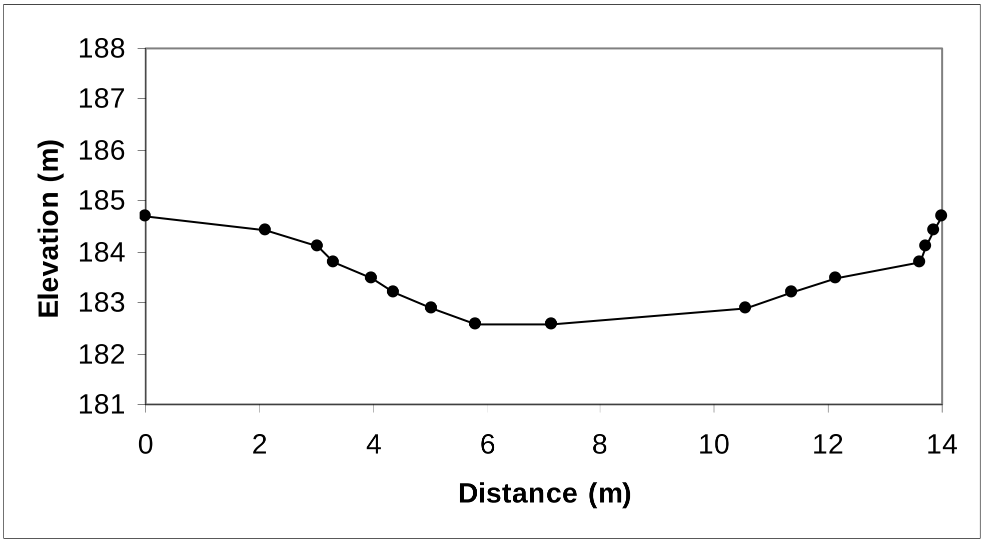

Figure B-34. Cross-section of Waller Creek at Shipe Park Riffle 2 from City of Austin topographic survey before restoration, 1995.

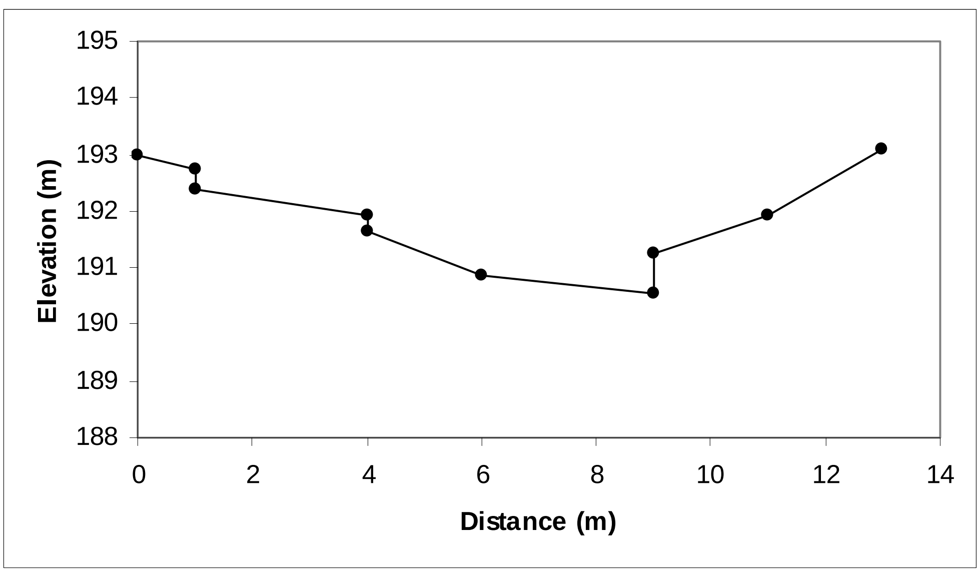

Figure B-35. Cross-section of Waller Creek at Shipe Park Riffle 2 after restoration, 2007.

APPENDIX C

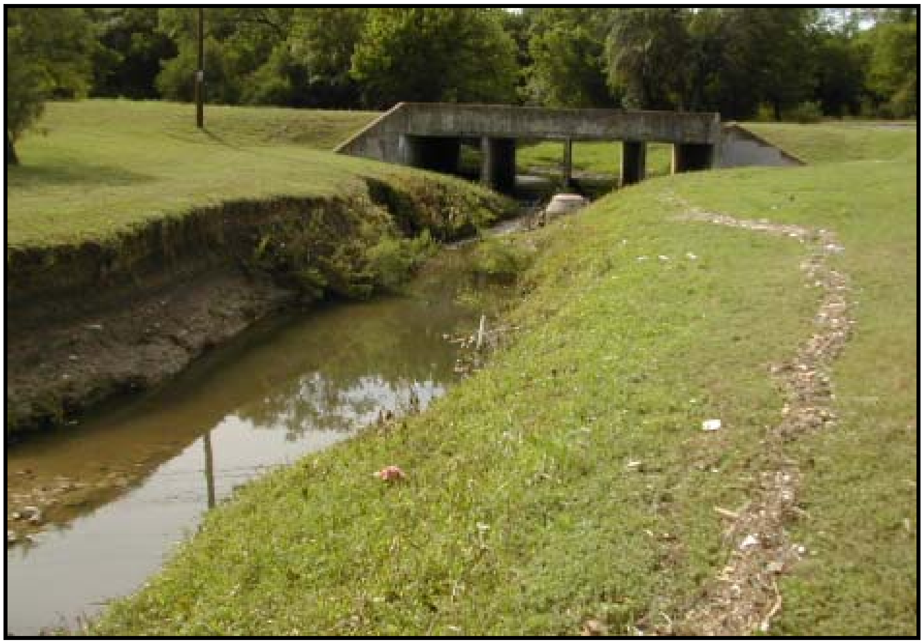

Figure C-1. Tannehill Branch in Bartholomew Park facing Berkman Drive before restoration, 2003 (Courtesy M. Rotar).

Figure C-2. Tannehill Branch in Bartholomew Park facing Berkman Drive after restoration, 2007.

Figure C-3. Tannehill Branch in Bartholomew Park facing Berkman Drive before restoration, 2003 (Courtesy M. Rotar).

Figure C-4. Tannehill Branch in Bartholomew Park facing Berkman Drive after restoration, 2007.

Figure C-5. Tannehill Branch in Bartholomew Park facing east towards pedestrian bridge before restoration, 2003 (Courtesy M. Rotar).

Figure C-6. Tannehill Branch in Bartholomew Park facing east towards pedestrian bridge after restoration, 2007.

Figure C-7. Tannehill Branch in Bartholomew Park downstream of pedestrian bridge before restoration, 2003 (Courtesy M. Rotar).

Figure C-8. Tannehill Branch in Bartholomew Park downstream of pedestrian bridge after restoration, 2007.

Figure C-9. Tannehill Branch in Bartholomew Park facing west towards pedestrian bridge before restoration, 2003 (Courtesy M. Rotar).

Figure C-10. Tannehill Branch in Bartholomew Park facing west towards pedestrian bridge after restoration, 2007.

Figure C-11. Tannehill Branch in Bartholomew Park facing downstream of pedestrian bridge before restoration, 2003 (Courtesy M. Rotar).

Figure C-12. Tannehill Branch in Bartholomew Park facing downstream of pedestrian bridge after restoration, 2007.

Figure C-13. Tannehill Branch in Bartholomew Park facing southwest towards swimming pool and parking lot on 51st Street before restoration, 2003 (Courtesy M. Rotar).

Figure C-14. Tannehill Branch in Bartholomew Park facing southwest towards swimming pool and parking lot on 51st Street after restoration, 2007.

Figure C-15. Head cut gully entering Tannehill Branch in Bartholomew Park east of white buildings before restoration, 2003 (Courtesy M. Rotar).

Figure C-16. Head cut gully entering Tannehill Branch in Bartholomew Park east of white buildings after restoration, 2007.

Figure C-17. Tannehill Branch in Bartholomew Park facing upstream behind baseball fields before restoration, 2003 (Courtesy M. Rotar).

Figure C-18. Tannehill Branch in Bartholomew Park facing upstream behind baseball fields after restoration, 2007.

Figure C-19. Tannehill Branch in Bartholomew Park facing north bank behind baseball fields before restoration, 2003 (Courtesy M. Rotar).

Figure C-20. Tannehill Branch in Bartholomew Park facing north bank behind baseball fields after restoration, 2007.

Figure C-21. Tannehill Branch in Bartholomew Park upstream of dam facing southeast before restoration, 2003 (Courtesy M. Rotar).

Figure C-22. Tannehill Branch in Bartholomew Park upstream of dam facing southeast after restoration, 2007.

Figure C-23. Tannehill Branch at Lovell Drive before restoration, 2005 (City of Austin, 2001a).

Figure C-24. Tannehill Branch at Lovell Drive immediately after restoration, 2005 (City of Austin, 2001a).

Figure C-25. Tannehill Branch at Lovell Drive after restoration, December 2007.

Figure C-26. Tannehill Branch upstream of Lovell Drive during installation of restoration practices, December 2007.

Figure C-27. Waller Creek in Shipe Park before restoration practices, facing 45th Street, 1995 (City of Austin, 2001a).

Figure C-28. Waller Creek in Shipe Park after restoration practices, facing 45th Street, December 2007.

Figure C-29. Waller Creek in Shipe Park after restoration practices, facing G Street, July 2007.

Figure C-30. Waller Creek in Shipe Park after restoration practices, facing G Street, March 2007.

Figure C-31. Waller Creek in Shipe Park after restoration practices, facing F Street, March 2007.

Figure C-32. Waller Creek in Shipe Park after restoration practices, facing F Street, July 2007.

Figure C-33. Waller Creek upstream of Shipe Park, March 2007.

Figure C-34. Waller Creek downstream of Shipe Park, July 2007.

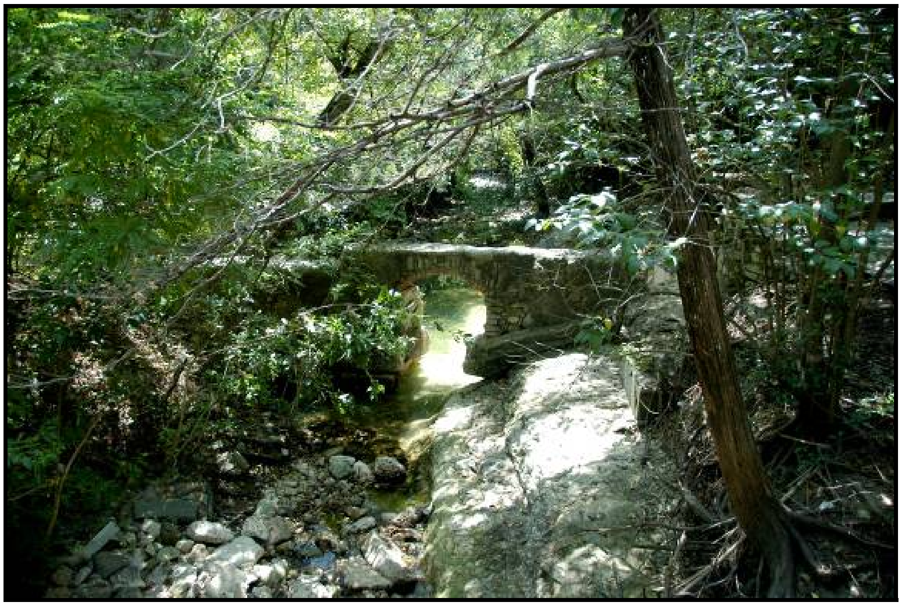

Figure C-35. Dam from 1800s behind Elisabet Ney Museum on Waller Creek, downstream of Shipe Park, July 2007.

VITA

Name: Megan Driskill Meier

Address: c/o Dr. Rick Giardino
Department of Geology and Geophysics, 3115 TAMU
College Station, Texas, 77843-3115

Email: mdmeier@ag.tamu.edu

Education: B.S., Wildlife and Fisheries Sciences, Texas A&M University, College Station, Texas, 2004

M.S., Water Management and Hydrological Science, Texas A&M University, College Station, Texas, 2008

Experience: Graduate Teaching Assistant, Ornithology and Ecology laboratories, Department of Wildlife and Fisheries Sciences, Texas A&M University, 2004 – 2005

Graduate Research Assistant, Water Management and Hydrological Science Program,
Texas A&M University, 2005 – 2007

Student Technician, Texas Water Resources Institute, 2007 – present

Posters: Post-restoration evaluation of urban streams in central Texas, Annual Meeting, Association of American Geographers, San Francisco, California, 2007

Post-restoration evaluation of two urban streams: Austin, Texas USA, Joint Annual Meeting, Geological Society of America, Denver, Colorado, 2007

Affiliations: Association of American Geographers
Geological Society of America